School of Science

Department of Imaging & Applied Physics

Testing Potential New Sites for Optical Telescopes in Australia

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To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Claire Hotan

To my father, who has always told me that education is never over.

I see mine still isn't!

Thanks Dad :-)

Problem Solving:

I lay claim to being a good problem solver. However, showing my mathematician heritage, that really only extends to seeing the existence of a solution, never mind the implementation.

That's not great for getting work done, because when I can see that it's possible to finish writing a chapter, well, that's "solved". But what's worse is that I will think "I'm thirsty", see the glass of water on my desk, think "ah, problem solved"and carry on with what I was doing. Only to repeat the process once again every few minutes. Eventually I actually realise that the water in the glass is the same water as was in the glass before and my problem is not solved, *but that can take hours.*

Brilliant.

- Rowan Martin-Hughes, 2009.

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To all those mentioned above, as well as all those who should be mentioned but I have forgotten to include, my sincerest thanks.

Abstract

In this study we aim to find locations in Australia capable of hosting a large optical telescope, ideally larger than our current premier instrument, the 3.9m Australian Astronomical Telescope, which may be built in the future to extend Australia's optical astronomy capabilities and create multi-wavelength ties with radio astronomy.

We are able to refine possible locations by studying remotely sensed meteorological data to ascertain expected cloud coverage rates across Australia, and combining them with a digital elevation model using a Geographic Information System software package. We find that the best sites in Australia for building optical telescopes are likely to be on the highest mountains in the Hamersley Range in Northwest Western Australia, while the MacDonnell Ranges in the Northern Territory may also be appropriate.

The current major optical astronomy site in Australia, Siding Spring, is good considering its proximity to major cities, but being located near the Great Dividing Range it experiences relatively high levels of cloud cover. We believe, however, that similar seeing values should be available and with more observing time at the proposed sites. We thus propose that a campaign of astronomical site testing should be undertaken on Mount Bruce and Mount Meharry in the Hamersley Range, and seeing and light pollution values compared to those measured at existing observatory sites.

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Chapter 1

Introduction

1.1 Aim of the Project

The aim of this research is to use image analysis techniques and Geographic Information Systems to consider variables affecting the sky quality across Australia to assess the suitability of various parts of the country as sites for optical telescopes. In particular we aim to make some judgement of the "goodness" of sites currently used for research-class observatories, and to propose potential sites for new instruments which may extend into the 8m reflector regime of large optical telescopes. In future work, studies should be done to follow up one or two candidate sites with a proposed remote monitoring programme. It is thought that Western Australia, with its large areas of desert, low levels of light pollution and relatively high altitude geographic features is likely to contain such a candidate site.

The primary objective of this research is to identify a candidate site as a location to build an 8m class optical telescope in Australia (although this suggested size is not particularly well determined, as will be discussed in the text). An implication of pursuing this objective is that we will also rate the locations of Australia's currently existing research optical telescopes in Bickley, W.A., Siding

Spring, N.S.W., Mount Stromlo, A.C.T. and Canopus Hill, Tas., in terms of site quality, based primarily on atmospheric conditions (such as cloud cover and rainfall) and altitude.

The Australia-wide testing will be done entirely with geographic and meteorological data. If we are successful in finding a site apparently capable of hosting a scientifically viable 8m class telescope, then future work includes building a remote sky monitoring station which will allow us to judge the quality of sky conditions at the site(s) for an appropriate period and making some comparison to other sites in Australia at a similar time of year. Even if a site which is suitable for such a large telescope is not found, it may still be possible for us to identify more scientifically valuable sites for research facilities in the 1–4m range, which would have different scientific goals than the putative large telescope, but which could potentially be of more value to the astronomical community in terms of their specific capabilities and proximity to large radio astronomy facilities. Such telescopes may have different requirements in terms of number of observing hours available or typical atmospheric conditions.

1.2 Background

Australia, having no significantly high mountains like those of Hawai'i and South America, is not home to any very large next generation optical astronomy observatories (unlike radio astronomy, in which Australia is a world leader). In fact, of the roughly 56 operational telescopes around the world shown in Figure 1.1[1] that have mirrors at least 2.2m in diameter (including the Hubble Space Telescope, in Low Earth Orbit, not shown in Figure 1.1), only 2 are located in Australia (Arnett, 2009) (three, if we consider telescopes at least 2m in diameter, though the total number increases proportionally). Although both of these telescopes have

[1] Data for this image are sourced from http://www.esri.com/software/arcgis/arcgisonline/standard–maps.html for the world map, and Arnett (2009) Large Optical Telescopes list, http://astro.nineplanets.org/bigeyes.html.

cutting edge instruments allowing them to do world class science, they are nevertheless smaller than 4m diameter and thus do not have the potential sensitivity of larger telescopes. Furthermore, in the coming years a number of next-generation telescopes of >10m effective diameter will be built.

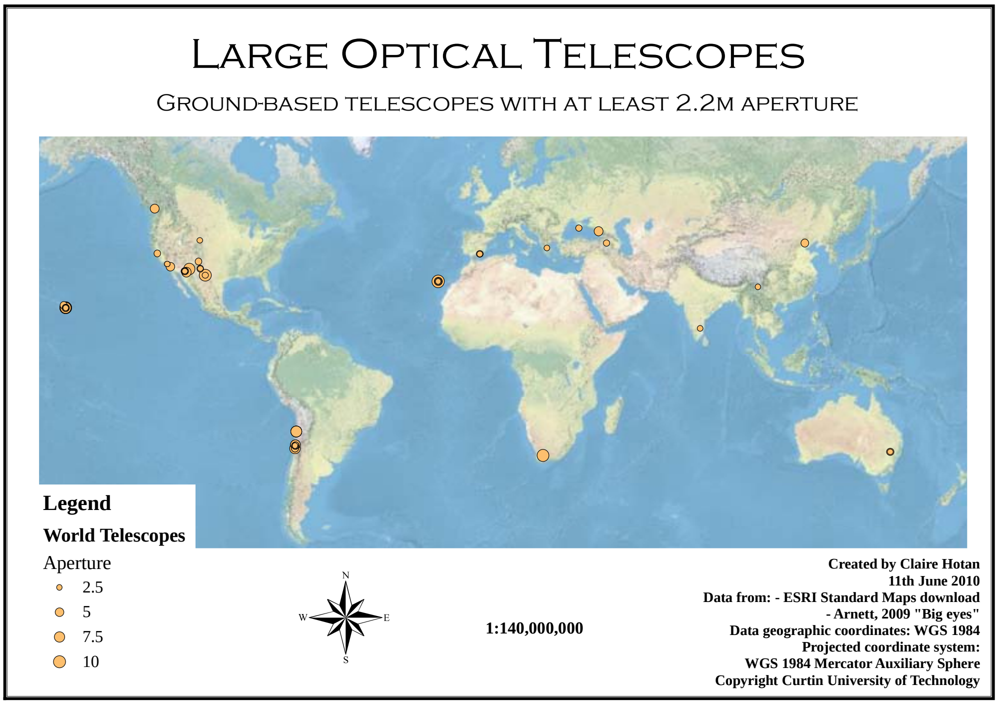

Figure 1.1: Map showing all large telescopes in the world with apertures $\geq$2.2m.

Currently, the major optical research site in Australia is at Siding Spring near Coonabarabran in northern New South Wales. This site hosts the Australian Astronomical Observatory and the Mount Stromlo Siding Spring Observatory (with other research telescopes located at Mt Stromlo, A.C.T., Canopus Hill, Tas., Bickley, W.A. and Gingin, W.A., see Figure 1.2. Some statistics on these instruments will be presented in Table 3.1). The Australian Astronomical Telescope (AAT) is located on this site and is the largest optical telescope in Australia. Unfortunately, despite being the primary telescope of choice for Australian optical astronomers, it often suffers reduced observing hours due to cloud obscuration and inclement weather. Thus it is desirable to search for a site with good seeing qualities and with less frequent and extensive cloud cover than Siding Spring. Figure 1.3 shows a night–time satellite image of Australia[2]. Australia has so little light pollution compared to the rest of the world that it is hard to see anything but the major cities in the whole world image that this figure is taken from. Even after enhancing the colour scale we still see that outside of the city areas, Australia contains significant areas of dark–sky sites which may provide excellent deep viewing of the night sky.

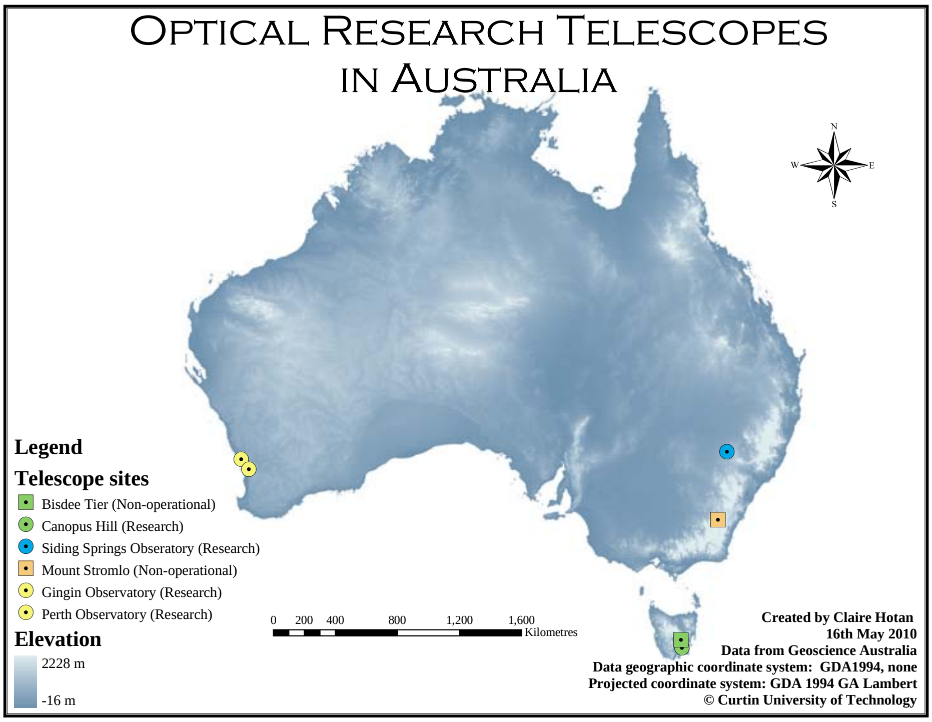

Figure 1.2: Map of Australia showing current large research optical telescopes.

Astronomers use the term "seeing" to indicate the clarity (and stability) of the atmosphere through which they are observing - hence the very good "seeing" at very high altitudes such as in Hawai'i and Chile (where the atmosphere is thin) (Chaisson and McMillan, 2005). To justify the possible construction of any

[2]Image taken from the NOAA satellite archive at http://www.ngdc.noaa.gov/dmsp/downloadV4composites.html

future large telescope in Australia, such a site would need to be an improvement on Siding Spring, and good enough to potentially host a world class 8m telescope. This site would need to have a high altitude and clear, stable atmosphere, with very little artificial light pollution. Western Australia, with its high inland ranges, sparse population, and prevalence of desert areas (hence low rainfall), seems an ideal location for such a telescope. In fact, the Satellite Laser Ranging (SLR) station in Yarragadee, W.A. ($29^o03'$S, $115^o21'$E, ~270m), is typically one of the best, and often the best, SLR stations in the world in terms of both data quantity and quality (Husson, 2003; Pearlman et al., 2005; Combrinck and Suberlak, 2007; Schillak and Lehmann, 2008). This indicates in part that the site has consistently good atmospheric and meteorological conditions, thus we might expect other similarly good sites in the area.

A preliminary meteorological analysis by Prof. Karl Glazebrook, of Swinburne University of Technology suggested Mt Bruce, W.A., as such a potential site (Glazebrook, 1999) (in hypothetical agreement with Dr. Andrew Cole (Cole, 2010) of the University of Tasmania), while based on similar analyses Wood et al. (1995) propose Freeling Heights in S.A., which is near the Mount Searle site tested in conjunction with Siding Spring by Hogg (1965); and Walsh (2004) suggests Mt Singleton in W.A. may also be of comparable "seeing" to both Siding Spring and Freeling Heights. This project aims to quantitatively further this investigation by conducting a study of Australian continental cloud cover, precipitable water vapour, altitude, population distribution, and a number of other geographic aspects, to *(i)* confirm the appropriateness of Mt. Bruce, *(ii)* potentially identify other possible locations and compare to existing locations, and finally *(iii)* conduct tests on the best site to directly measure its "seeing" (considered future work to this project).

As large telescopes (operating at any wavelength - radio, optical, x-ray, etc.),

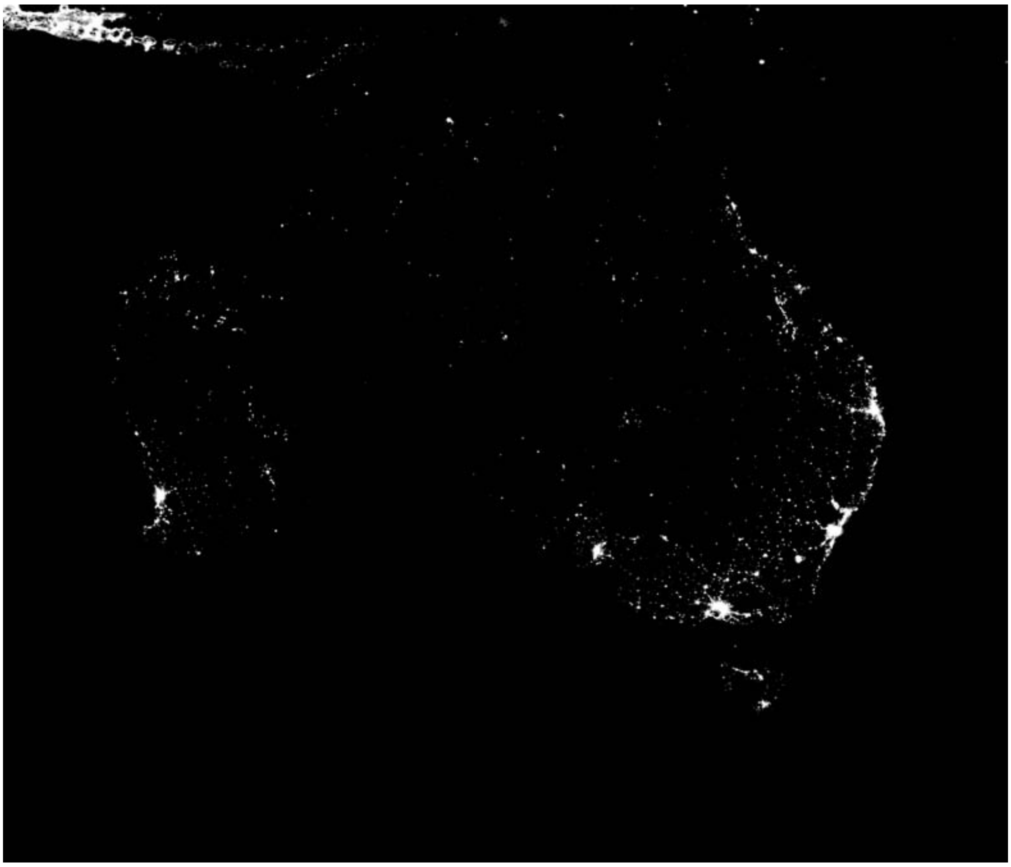

Figure 1.3: Night–time image of Australia showing stable sources of light pollution in 2009.

require a significant expenditure to build, and need to produce the best science possible, it is vital that the time be taken to choose the right location. Any location will by necessity have some downtime associated with the operation of the telescope, both due to breaks for maintenance, and sky conditions (by its very nature the majority of optical astronomy can only be done at night!) including clarity of atmosphere and operability of telescope given prevailing winds. Both maintenance downtime and observability downtime are important. A very remote unmanned telescope will take significantly more time to repair than one which is continually manned and "near civilisation". For example, there is a proposed telescope to be built in Antarctica (Burton et al., 2005), which has many clear advantages in terms of seeing and low atmospheric extinction in the IR bands, but with only approximately 4 dark months a year it may have less absolute observing time available than a non-polar telescope, and would not in general be available for rapid-response multi-wavelength follow-up observations. This is compounded by the situation where if any damage were to occur to the telescope during the observing season - winter - when maintenance is severely hampered, most of that observing season may be lost waiting for it to become light again!

At a diameter of 3.9m, the Australian Astronomical Telescope at the Australian Astronomical Observatory (AAO) at Siding Spring is the largest optical astronomy research instrument in Australia (Anglo–Australian Observatory, 2006), however due to unfavourable cloud cover or precipitation, it is closed due to weather on average around 35-40% of the (night) time, with photometric (ideal clear sky) conditions for only 40% of the remaining observable time (Anglo–Australian Observatory, 2006; Tinney, 1996). That is, the AAO has photometric conditions around 25% of the time. In comparison, facilities such as the Keck Telescopes and Gemini North on Mauna Kea, Hawai'i, U.S.A. experience 25% weather downtime (Bely, 1987) while having photometric conditions up to 62% of the observable time ($\sim$ 45% of the total time) (Puxley, 2001). While in Chilé in South America, Paranal Observatory which houses the Very Large Telescope

(VLT) experiences 27% total lost time, with photometric conditions as often as 75% of the observable time (Sarazin, 2010).
In terms of radio telescopes, where Australia is a highly favoured site due to the visibility of the centre of the Milky Way from the Southern Hemisphere, there are two major meteorological factors (below ~10GHz observing frequency above which atmospheric water vapour becomes a problem). These are phase changes due to the ionosphere at low frequencies (affecting arrays in particular); and wind, as the older very large dishes act like sails, it is unsafe to use them when the prevailing winds climb above around 40km/hr (or gust above 50-60km/hr). Sites used for radio astronomy typically have weather limitations of less than 5% of observing time in Australia (Chapman, 2006; Reynolds, 2004), due both to wind and to electrical storms. Thus we see it is important to consider not only political and accessibility factors when choosing a site for a telescope, but also the atmospheric environmental conditions, both in terms of clarity ("seeing" for optical telescopes, "radio quietness" for radio telescopes), and also average, and where possible extreme, weather conditions that will play a part in the usable time fraction for the telescope.

Geographic and meteorological studies into telescope siting have been done in the past (Ardeberg, 1983; Coops et al., 1991; Graham et al., 2005; Hogg, 1965; Mills et al., 1958; Zhu et al., 2001). Historically, however, such studies were temporally very limited, and frequently did not have access to the computational facilities required for a full analysis if appropriate data were even available. For example the Parkes radio telescope operated by CSIRO ("The Dish") was built in 1961, before the geographic analyses proposed here were practicable, and so despite a rigorous site selection process (Mills et al., 1958) based on proximity to Sydney, radio–quietness and planned development in the area, and availability of land (and willingness of the local council), only secondary heed was paid to matters such as weather (both in terms of wind loading, and potential snowfall adding significant weight to the dish). Thus despite a long process of assessing various proposed sites, considerations such as meteorology were determined as much by local hearsay as by science. Consequently the Parkes site, which was believed to be very calm, has ever since its official opening (Robertson, 1992), experienced significant and sometimes frequent periods of "wind stow". While this is not being considered in this investigation, it is perhaps worth noting that today a more thorough analysis would be possible at little cost which would more quantitatively show whether or not this site was a "good" choice.

With current data sets, climate models, and computing facilities, we can make choices more informed on virtually all fronts in the future, importantly meteorologically, and to this end the University of Friboug, Switzerland, has created its own Geographic Information System for the purpose of telescope siting questions, designed with the project of selecting a site for the proposed European Extremely Large Telescope (E–ELT) in mind (Graham et al., 2005; Sarazin et al., 2006).

1.3 Significance

If a site were found with significantly superior viewing conditions to those prevalent at Siding Spring, which was accessible and power could be supplied relatively easily, it would pave the way for the possible future construction of a new large telescope in Australia. This would have clear advantages to the Australian astronomical community, in terms of producing leading research, and furthermore, reducing our scientific reliance on international collaborations using telescopes overseas. Such telescopes are often heavily oversubscribed, meaning that while we would still not have our own Very Large Telescope, we would nevertheless be less reliant on small time shares of instruments to do leading research. The proposed telescope, depending on the locations available, might be of particular interest for multi-wavelength investigations with new radio astronomical facilities being built in Australia such as the Australian Square Kilometre Array Pathfinder (ASKAP) (Johnston et al., 2008), the Murchison Widefield Array (MWA) (Lonsdale et al., 2009) and potentially the Square Kilometre Array (SKA) (Dewdney et al., 2009).

Such a telescope would also be much more readily accessible than those in South America, which whilst being at very much higher altitude than Australia, is also much more remote in terms of access time for upgrades and maintenance, with a similar accessibility and maintenance argument applying to any telescope which may be built in Antarctica such as that described in the PILOT (Pathfinder for an International Large Optical Telescope) proposal (Burton et al., 2005), although it must be noted that PILOT would have different scientific goals to any large optical observatory being built on the Australian continent.

1.4 Outline of this Thesis

The research method employed in this project is primarily qualitative, involving a low-resolution Geographic Information System style Multi-Criteria Decision

Analysis (Figueira et al., 2006; J.MCDA, 2010; Longley et al., 2005; Malczewski, 1999) being performed across Australia to identify candidate regions, using data freely available from the Bureau of Meteorology[3] and Geoscience Australia[4]. The meteorological data are initially analysed using basic image analysis code written by the candidate, using the Python[5] programming language. A full description of this process is found in Chapter 2 of this dissertation.

Multi-Criteria Decision Analysis (MCDA) is performed using industry standard software, ESRI ArcGIS v9.3[6], into which the Geoscience Australia data can be readily loaded and analysed, with the meteorological data being rectified into a useful standard projection as appropriate. Once all relevant datasets are present and correctly projected they can be added together in a number of ways to show the effects of different "suitability" metrics. Details of this process can be found in Chapter 3.

Although time was not available during the execution of this research, in the future, field trips should be made to the best candidate site(s) to set up a remote testing station which could collect data on cloud cover and visibility, and thus confirm or refute the site as a suitable one for an optical telescope installation. Ideally this analysis would also be performed at an existing site to confirm our measurement accuracy. Discussion of such studies are found in Chapter 4.

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[3]The Australian Government Bureau of Meteorology (BoM) website, Geostationary Satellite Data Archive, ©Commonwealth of Australia, http://www.bom.gov.au/sat/archive_new/gms/.

[4]Geoscience Australia (GA), Free Data Downloads, ©Commonwealth of Australia, https://www.ga.gov.au/products/.

[5]Python Programming Language, http://www.python.org/.

[6]ESRI website, makers of ArcGIS software, http://www.esri.com/.

Chapter 2

Meteorological Analysis

2.1 Why Meteorological Analysis is Important in Choosing a Telescope Site

When choosing a site to build an optical telescope, one of the main questions to ask is, how often can it be used? Clearly, the less cloudy a site, the more time can be spent making astronomical observations. As such, we wish to select sites with minimal cloud cover during the night time. Therefore, we consider cloud cover as a proxy for the amount of observing time available at a site. Furthermore, in some senses the amount of cloud cover will also indicate the clarity of the atmosphere at that site, as thick cloud will fully obscure viewing, but some limited observing modes may still be possible through diffuse cloud. Ideally, we wish to know not only how often a site is cloudy, but the types of cloud present. If a site were found with no cloud cover, then it would have very good potential as an observing site, so long as the air column above the site was relatively stable.

These considerations have been studied in the past when looking at potential telescope sites, and the paper of Coops et al. (1991) discusses different mechanisms for collecting and analysing cloud cover data, both in terms of ground based measurements but also using satellite imagery, which the authors go on to suggest indicates two good regions in Australia – in the northern Flinders Ranges

(S.A.) and the Hamersley Range (W.A.). Coops et al. (1991) did their work when satellite imagery was not readily available in a consistent format over long periods of time, and a number of different "cloud climatologies" were used to investigate cloud cover over Australia. As Coops et al. (1991) took a particularly meteorological perspective to site selection, the authors discuss mechanisms by which cloud type may be identified in both ground-based and satellite observations, noting that both will have uncertainties, but that it should in principle be possible to classify roughly the cloud types and thus extinction expected.

A number of variables must be taken into account when considering the siting for a telescope, as discussed by Ardeberg (1983) wherein the author creates a list of 19 parameters in 4 categories which must be considered when siting a telescope. The first category considered by Ardeberg (1983) (and subsequent papers by the same author) is that for which the parameters are of an atmospheric nature – that is, where we are concerned with meteorology. The seven parameters identified in this category are cloudiness, air dryness, precipitation, atmospheric turbulence (seeing), scintillation, wind and extinction. Thus we see that cloud cover is considered of primary importance in choosing a telescope site. To quote Ardeberg (1983), *"A high number of both night-time and day-time hours with a sky free of clouds is an absolute necessity before any place can seriously be considered as a candidate for the site of a modern astronomical observatory."*

In this chapter we discuss the remotely sensed meteorological data used for this study (2.2.1), as well as other types of remotely sensed data available (2.2.3), and how the data used have been analysed (2.3.3) to create a map which can be used for site suitability assignment (2.4). Taking advantage of more recent technological developments in this study, rather than creating a map of isonephs (lines of constant cloud cover rate), we produce colour-scale maps indicating cloud coverage at all points across Australia.

2.2 Meteorological Data used in this Study

In this investigation we have used only data freely available for download from the Australian Government Bureau of Meteorology, who do not own the satellite from which the data are sourced, but who release the data products publicly. Other sources of data at different resolutions and wavelengths are available from various sources, some are free, some require a subscription fee for data access. Indeed, this is also true for the Bureau of Meteorology (henceforth "BoM"). Long term data archives are only available on request and for a fee, so in this study we have limited ourselves to those data which can be freely and readily obtained. Acquiring the longer period archives, or other wavebands, would require a custom data retrieval request for which the BoM charge an amount exceeding that available to a research student.

2.2.1 Remotely Sensed Meteorological Data

There are a number of geostationary and polar satellites in orbit collecting meteorological data or relatively recently decommissioned from this task, such as GOES–9 (operated by both the Japan Meteorological Agency (JMA) as a temporary replacement for GMS–5, and the National Oceanic and Atmospheric Administration (NOAA) of the USA until its decommissioning)[1], the JMA's MTSAT–1R[2] which replaced the Geostationary Meteorological Satellite GMS–5 and GOES–9, China's Feng Yun 2, FY–2[3], as well as the USA's Defence

[1]Outdated information about the temporary change-over from GMS–5 to GOES–9 can be found at http://www.bom.gov.au/sat/gms_backup.shtml
but note that the satellite was permanently decommissioned in 2007.

[2]Information from the BoM may be found at
http://www.bom.gov.au/sat/MTSAT/MTSAT.shtml.

[3]A brief description from the BoM can be found at
http://www.bom.gov.au/satellite/paper1Other.shtml#FY–2.

Meteorological Satellites Program (DMSP)[4], all of which have been accessed in the process of this research. Other meteorological satellites exist and collect, or have provided, a regular data service. However those satellites listed above are predominantly used by the BoM and have fields of view adequately covering Australia. Another satellite not used in this study is MODIS[5] which also produces relevant data, particularly for precipitable water vapour.

Indeed, satellites which do not fully cover Australia with each image are of no use to us as we are only considering siting in Australia and we want reliable datasets. Different satellites carry different instruments, so not all satellites necessarily observe at the same wavebands, though typically they do carry detectors in the visible regime and IR covering both cloud cover and precipitable water vapour, so data should be reasonably consistent. However, if data from multiple satellites are used in a study, it is important to ensure the consistency of the data across the change-over period.

The time period in which data were acquired for this investigation was June 2008 until January 2010. For the entire duration of this period, the Japan Meteorological Agency's MTSAT–1R has been the primary (indeed only) data source provided by the BoM. As no data were acquired prior to MTSAT–1R being commissioned, our data are readily comparable as all images are taken at the same waveband. The decision to use only one waveband from one satellite is in fact the same approach taken by Coops et al. (1991), who used a previous generation of Japanese satellite data provided by the BoM over a 3 year period, also at infrared wavelengths to enable night-time coverage.

[4]The Defense Meteorological Satellites Program information may be found at http://heasarc.gsfc.nasa.gov/docs/heasarc/missions/dmsp.html.

[5]MODIS is the MODerate resolution Imaging Spectroradiometer operated by the USA to study global dynamics, information can be found at http://modis.gsfc.nasa.gov/data/.

2.2.2 Charactersitics of Infra-red Wavelength Data

We have chosen to work with infrared (IR) wavelength data, that is, the $10.3 - 11.3\mu m$ waveband. This wavelength is sensitive particularly to cold atmospheric responses, and this is a good tracer of cloud cover, in particular high altitude cloud. There are two significant advantages to using IR data rather than visible. Most notably, IR wavelengths can return readings at any time, and thus while there may be some diurnal variation in the magnitude of response, images can be produced 24 hours a day. This is particularly important as we want an optical telescope to work at night, but the satellite of course cannot produce visible wavelength images while on the night side of the Earth, and therefore there are no night-time images at these wavelengths. We ideally want to consider cloud cover both during the day and during the night, and thus visible wavelength data are not appropriate for our task. Furthermore, visible data traces predominantly low level cloud, which is more likely to be detrimental to the task of astronomical observing than diffuse high-level cloud, but we are interested to know when the sky is entirely free of cloud which visible data alone cannot tell us. Thus it is advantageous to look in a waveband that picks up the higher, more diffuse cloud as well as producing some response to the heavier rain–bearing clouds, as this will give a better indication of how much of the time is likely to be photometric (that is, completely clear)[6].

The MTSAT–1R satellite has 5 wavebands of detection, one visible and four infrared wavelengths, however only two of these are made available at higher resolution by the BoM, one being visible, the other infrared[7]. Thus we have chosen to use the infrared wavelength data for our analyses.

Of course, it must be noted that the infrared data used here do not provide a

[6]See, for example, information on how various cloud types appear at visible and infrared wavelengths from the University of Wisconsin-Madison
http://cimss.ssec.wisc.edu/sage/meteorology/lesson3/concepts.html.

[7]The Japan Meteorological Agency provides information on its satellites at
www.jma.go.jp/jma/jma-eng/satellite.

stand-alone ideal data source. While IR traces even quite diffuse cloud, it does not detect the thicker cloud that is seen in visible wavelengths as strongly. Furthermore other frequencies in the infrared regime effectively trace other atmospheric conditions, so ideally we would consider a number of different wavebands in our analyses. Unfortunately due to both data availability and time constraints, that has not been possible in this study, but it is considered an important extension to the work presented here.

2.2.3 Types of Data

Meteorological data may be acquired in a number of ways, remotely sensed from space, by sensors deployed at stations in various locations, or directly observed by eye. For this analysis we have only used those data acquired by meteorology satellites, as by their nature they give even coverage across the continent and are thus best suited to our task – meteorology stations are not necessarily already in place in the areas we may be interested in for this study. Thus in this section we will predominantly discuss data types available from the MTSAT–1R satellite that is provided by the BoM with hourly resolution, although we will also touch on some ground-sensed data which is worthy of note in this study.

As mentioned above, meteorological satellites typically observe at a range of wavelengths. The satellite whose data we have used here, MTSAT–1R, carries sensors in 5 wavebands:

- **VIS** (Channel 1), $0.56 - 0.80\mu m$, visible
- **IR1** (Channel 4), $10.3 - 11.3\mu m$, infrared 1
- **IR2** (Channel 5), $11.5 - 12.5\mu m$, infrared 2
- **IR3** (Channel 3), $6.5 - 7.0\mu m$, water vapour
- **IR4** (Channel 2), $3.5 - 4.0\mu m$, near infrared

Of these wavebands, we are most interested in channels 1, 3 and 4, as these show visible data, infrared data (as discussed previously), and shorter wavelength infrared which traces atmospheric water vapour. These data are available from the BoM but a subscription fee applies to the data in channels 2, 3 and 5, which is in large part the reason we have not investigated water vapour data.

Channel 3: IR3 observes in the 6.5–7.5μm wavelength range. Water vapour absorbs strongly at these frequencies, meaning that the atmosphere is opaque to this radiation if there is any water vapour in the path (Campbell, 2007). Thus, acquiring data at these wavelengths (as well as in a few windows below approximately 1μm) allows us to trace the atmospheric abundance of water vapour. Analyses comparing the values at these wavelengths with cloud cover data at other wavelengths allows the creation of Precipitable Water Vapour (PWV) data sets. Using MTSAT–1R data we would need to create these algorithms ourselves, but using the MODIS satellite data products instead, PWV could be accessed directly[8] from a different water vapour absorption line, using an algorithm developed by Gao and Kaufman (1998). This is considered beyond the scope of this study, but this is an important extension of the work, which should be carried out before any final conclusions are drawn in the case of a telescope siting going ahead.

Channel 1: VIS is the MTSAT–1R channel which operates in the visible wavelength regime. Visible wavelength imagery can be considered a good metric for investigating cloud cover, as it is by its nature quite analogous to what an observer on Earth would detect, though of course more likely to detect higher altitude cloud than lower altitude cloud, the opposite of a ground-based observer's problems (Coops et al., 1991). In this sense it seems like a logical dataset to use as it will be compatible with data taken using any naïvely developed remote

[8]The MODIS product description for Precipitable Water can be found at http://experts.nasa.gov/MOD05_L2/index.html.

monitoring station (such as a webcam). Unfortunately, however, both approaches suffer the distinct disadvantage of only returning meaningful data during daylight hours, and being effectively unusable at night. Because an optical telescope can only observe at night, we are very interested in measuring in particular night-time cloud cover, so using visible wavelength data is of far less practical use in this study than wavelengths that are available 24 hours per day.

Other data types

There is no fundamental reason to limit this study to directly sensed data from satellites. Derived data products and data observed at stations on the ground are also very important, and if available, should be taken into consideration. We have not done so here as the time frame of this work did not permit us to build our own monitoring station(s), and BoM observation points do not cover the country in a regular grid, and in fact are particularly sparse in regions of interest for building telescopes! However, a combination of derived information from satellite data, and interpolation of ground-based data, permits the production of other potentially useful metrics such as precipitation and wind strength and direction.

Rainfall data is of some interest to us in siting a telescope. We wish to know what amount of rain a location is likely to receive both long term and short term. The total amount of precipitation per annum will give some indication as to the goodness (or quality) of the observing site; however it is important to know about seasonal variations – is the precipitation evenly spread throughout the year, or does it fall on the in the winter months, or summer months (according to latitude)? Studying cloud cover data tells us how often a site is able to be used for observing, which ultimately is perhaps more important. Nevertheless, considerations such as general atmospheric moisture, or likelihood of flooding, are very important. Continental rainfall maps are available from the BoM covering a range of time periods[9]. These have not been quantitatively included in our analyses, but images like those shown in Figure 2.1 are important to consider at least qualitatively, where we see that total annual rainfall is concentrated along the East coast, tropics, and Southwest corner of the country, but falls predominantly in the Summer months in the tropics but in the Winter months at the lower latitudes.

Wind maps are available from the BoM in two forms, although other wind charts may also be derived. There are two approaches to considering wind: We may consider the wind across a large area (such as the Australian continent), or we may be interested in wind patterns at a certain point. In the first case, we can look at monthly wind patterns across the continent at various altitudes, to endeavour to gauge not only the strength of winds in various areas, but also their direction. From an astronomical perspective, our site does not necessarily need to be especially calm for an optical telescope (unlike for a large radio telescope), because a constantly moving air column, if it is nearly always moving in a constant direction at a constant low speed, will produce much better seeing than a still air column that is prone to diurnal convection currents, or a turbulent air current (McInnes et al., 1974). Laminar flow is often found across mountains in Western coastal areas of continents, and when available, provides an important advantage in astronomical seeing (McInnes et al., 1974). Mount Wilson in California, USA, is such a site, and regularly is capable of excellent sub-arcsecond observing due to the airflow over the observatory (Cowles, 1991; Hale, 1905). Similar arguments are put forward in favour of the Dome C site in Antarctica for an observatory (Lawrence et al., 2004). Excellent wind conditions are considered very important in siting the European Extremely Large Telescope (E–ELT), and so wind studies are included with seeing studies by Varela et al. (2006).

[9]These maps can be made and downloaded from the BoM climate data website at http://www.bom.gov.au/climate/averages/maps.shtml.

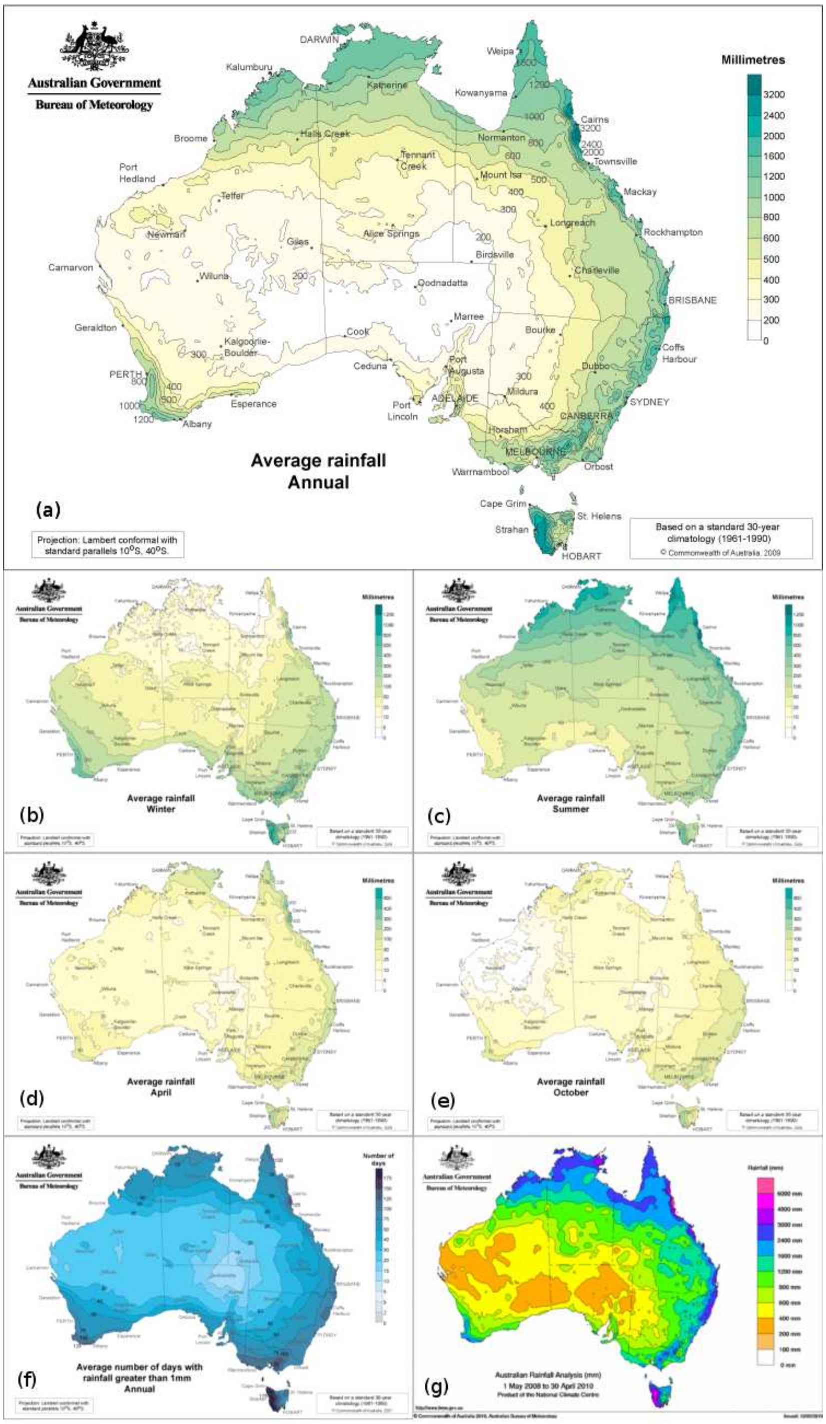

Figure 2.1: Maps showing rainfall across Australia. *(a)* Average annual rainfall, *(b)* Average winter rainfall, *(c)* Average summer rainfall, *(d)* Average April rainfall, *(e)* Average October rainfall, *(f)* Annual average number of days with >1mm rainfall, *(g)* Total rainfall in the 24 months 1st May 2008 to 30th April 2010.

Both types of data mentioned above, continental and site-based, are available from the BoM. Each observing station has an anemometer which records wind speed and direction, and from this data "wind roses" are created for each site with a sufficiently long data history[10]. We can also look at air movement across the whole continent at various altitudes, to obtain information such as that shown in Figure 2.2 from the BoM[11].

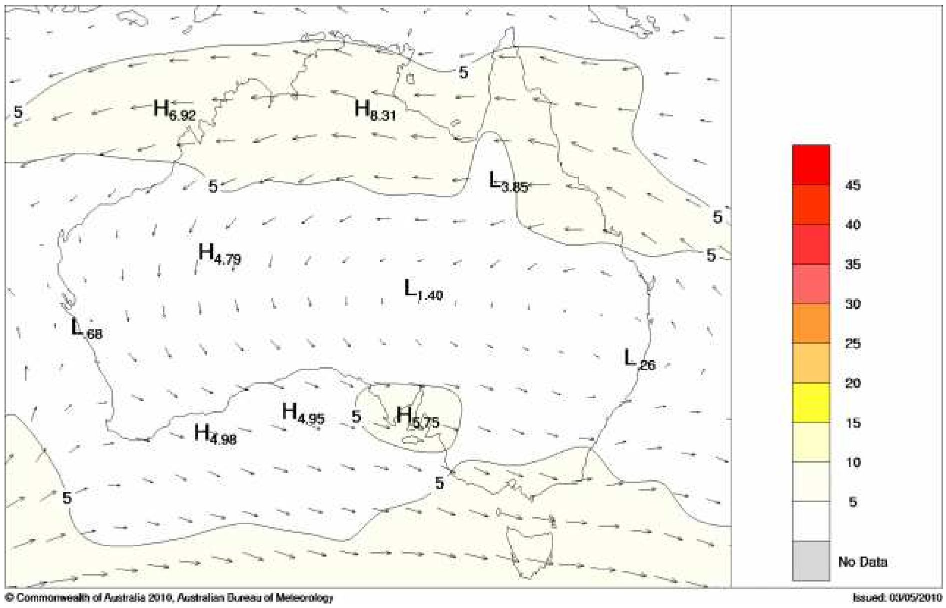

Figure 2.2: Map showing air movement (wind) across Australia at 850hPa averaged over April 2010.

[10]Wind roses can be accessed from the BoM using this page for all sites with >15 years of wind data http://reg.bom.gov.au/climate/averages/wind/selection_map.shtml.

[11]Wind coverage data can be accessed from the Atmospheric Circulation Patterns part of the BoM Climate data, for example 850 hPa monthly data for the last 10 years is available from the BoM FTP server
ftp://ftp.bom.gov.au/anon/home/ncc/www/cmb/850wind/mean/month/colour/history/nat/.

2.3 Acquisition and Analysis of Meteorological Data

2.3.1 Meteorological Data Acquisition

The Bureau of Meteorology hosts a website from which images may be downloaded free of charge[12]. These images are sourced via the BoM from the Japan Meteorological Agency's satellite MTSAT–1R and when acquired through the website, are of a poor resolution, roughly 30km per pixel. The resolution effects, however, are worsened by the superimposed global map, which has significant aliasing effects in the areas around it. These data were nevertheless acquired and some analysis done on them, as discussed in Section 2.3.2.

Through making enquiries with the BoM (Willmott, 2008), we learned that higher resolution images from the same satellite are also available for download from an FTP server[13], having an archive history of 20 days only. Thus it was necessary to download satellite images approximately every 2 weeks for a period of slightly over 18 months. In late January 2010 the server appeared to suffer some problems and more than twenty days passed without a data download. It was thus decided to call our data set complete at this point, having a dataset covering the period 11^{th} June 2008 to 22^{nd} January 2010.

We thus have two data sets, a low–resolution data set spanning multiple years (2004 – 2008), and high–resolution data spanning 19 months.

2.3.2 Methods Used - Acquisition

Data was acquired from the BoM in two ways. The first was the lower resolution "full disc" data, the second the higher resolution imagery showing only Australia.

[12] Images are searched for from http://www.bom.gov.au/sat/archive_new/gms/, however an automated approach is possible.

[13] FTP, or File Transfer Protocol, is a network communications protocol typically used for downloading raw data.

The BoM satellite data archive for preview returns many thousands of files, which would take months to meticulously download by hand. Instead a script has been written to execute the same task. Because these data are freely available, we believe it is reasonable to automate the process in this way. However, a script acquiring a large series of data files in one go would potentially disable a server and prevent other clients from accessing the data, so we use the linux command `wget` combined with a delay between each file to minimise stress on the server. The catalogue of files available dates back to January 1^{st} 1994, and are available through to the present. Not all the data are useful to us however, due to gaps in availability, non-standard time-stamp file names, or changing landmass outlines.

Trial Image - Low Resolution

The first step was to download just one image to investigate how we should proceed. The images are JPEG format, 30–40kB large, and in black & white. The images cover the "full disk" (half globe), and are acquired every 30 minutes, though not every image is full disk, many sample only the northern or southern hemisphere. Thus Australia is not visible in all images, so once we have our dataset, we need to be able to filter out images that do not have any data in the Southern Hemisphere. Some images are also corrupted, which can be harder to automatically identify.

The superimposed outline of Australia allows us to make some estimate of the pixel size in these images. Taking a readily identifiable feature of a known size, and counting how many pixels it covers (ideally over a few sample images) we can estimate the size of the pixels. In the sample image used here (midnight UT, January 1, 2008), King Island in Bass Strait covered 2×2 pixels. In practice, the island is roughly 64km from North to South, and 27km from East to West. We can consider a situation where the island is centred at the conjunction of 4 pixels, so that each of those pixels is roughly 30km square and contains coastline. Repeating this process with a few other locations, an estimate of ~25km $\times$ 25km pixels seems reasonable, though it is important to note that there are projection effects in displaying an image with significant Earth curvature in a flat array, so that the pixels will be close to square on the ground near the equator, but will become progressively more skewed at greater latitudes. While this resolution is very low, the mainland of Australia is very large, so it seems reasonable to expect that even with this implicit uncertainty, we may be able to construct some useful images. We find that the images are pre-processed so that geo-referencing by the user is not required.

An alternate method for estimating pixel size in these images is to use some tool that accurately gives a linear projected distance on the ground from a map, such as the Measure tool in ESRI ArcMap software. Identifying a feature that allows a certain latitude or longitude to be found in various images, the number of pixels in the country at that constant latitude or longitude may be counted by checking the pixel values of each coast at that x or y value in some image processing software such as GIMP[14]. We can compare this number to the distance across the country at that coordinate from the measuring tool in the mapping software, allowing us to calculate the value of $km/pixel$ (map scale). This method gives results in agreement the previous method.

Data Periods

The original data, dating back to 1994, were acquired with the GMS–5 satellite. When this satellite failed in 2003 it was temporarily replaced with GOES–9. This changeover potentially could cause data instability issues around the time of the change, so we would need to investigate whether analyses over that period are reasonable. However, there are gaps in the GOES data, with some images missing, and many having pink, then grey, landmass outlines rather than white after a gap of approximately 1 year between 2003 and 2004. The changeover to MTSAT–1R seems to have occurred in July 2005.

[14]GNU Image Manipulation Software, http://www.gimp.org/.

After inspecting data from a range of time periods and checking for consistency of filenames and coastline borders, it was determined that the longest contiguous dataset would be to gather data from June 2004 through to 2008, using the IR1 data. This relates to nearly 70 000 images.
These images were attained, as mentioned above, using the `wget` command, automated by a Python script, `BoM_file_retriever.py`, found in Appendix A.1.

Higher Resolution Data

After advice from Willmott (2008) from the BoM, we decided to also acquire a shorter time range of higher resolution images from the BoM FTP server. These were attained manually approximately every two weeks, by logging onto the BoM server (`ftp ftp.bom.gov.au`), and running `mget` on the GMS directory, containing visible, infrared, and false-colour composite data.

2.3.3 Methods Used - Analysis

To investigate cloud cover we wish to know where the cloud is in each of our satellite images, according to pixel value. Images can be queried and manipulated in a number of ways. The three which are of the most use to us are *(1)* using a Geographic Information System package, *(2)* using image processing tools in a package, or *(3)* using image functions in a programming environment.
(1) A Geographic Information System (GIS) (discussed in Chapter 3) allows us to load images as "raster" data layers (that is, grids), and query each pixel for its value. This will be very useful to us when we have our final combined image, however using a GIS to create this combined image is possible, but not computationally efficient compared to methods (2) and (3).
(2) Another option is to use existing image processing routines such as are available in numerical mathematics packages such as MATLAB® or IDL®, as well as their free counterparts Octave or GDL (open source mathematical analysis programs allowing similar analyses), and also as add-on modules to languages

such as Perl and Python[15]. Using any of these programs or modules, we can use existing libraries to load the image as an "array" where each element in the array carries the value of the equivalent pixel (this involves interpretation of the JPEG file format). Combining the images can then be done using built-in functions in these programs or modules.
(3) The final option mentioned is to write our own image addition algorithms in a programming environment. Ideally we should get the best efficiency, though this may not be readily measurable with current processor speeds. Image addition can be a memory–intensive task, if we minimise the amount of software overhead in our analysis we should be able to run computations faster. Thus the fastest way to combine images should be to use a programming language. This method involves significant development overhead to write routines to read images from disk and perform decompression and manipulation tasks on them. This development overhead needs to be considered as a time efficiency aspect of the overall project.
Thus I have chosen an option somewhere between methods *(2)* and *(3)*. I have chosen to use the image processing module available for Python to load and interpret the images, but have written my own algorithms to add them together using a function that combines two images with some weighting. This is discussed further in the following paragraphs.

An important consideration in analysis is whether our images are stable over the period in which they are acquired. If there is any significant change in the algorithm producing the landmass outlines, or in the position of the satellite, we might expect some shift in the datasets so that adding them directly is not possible, but rather cross-correlation between images is required to bring them into line. Initially it was suspected that this might be necessary for every image,

[15] Perl and Python have additional modules which can be used, PDL (Perl) and NumPy and PIL (Python), which give them similar though lower-level capabilities to software like IDL.

however in practise the datasets are rectified before release, and so it appears that there are at worst only minor changes between images as coastline is occasionally detected differently. Upon investigation of a number of images it was apparent that the small further loss in resolution associated with potentially blurring the coastline would be both easier and as accurate as attempting to cross-correlate and shift images.

Low-resolution Data

The low-resolution full-disc data were numerous, but a number of these images did not contain any data for Australia, being images of the Northern Hemisphere only. Thus the first step in processing these data was to filter out all images where no data covered Australia (interpreted as the pixel values for a number of sites across the continent were all close to 0). Those files with valid data were then cropped to the size of Australia only, to minimise memory costs when combining the images. Both these steps are done using a script called `filter_ims_Aus_not_0.py`, which is presented in Appendix A.2.

The next step was to sum these cropped images together. Two possible algorithms were considered to do this, and thus a script was written that implemented both. The script which produces the combined and averaged images (`sum_IDE00009_cuppa.py`) may be found in Appendix A.3.
We use the Image module[16] from the Python Imaging Library[17], and the function `Image.blend(file1,file2,`α`)` which takes two images and a weighting value as input, and outputs an image that is produced by $(1-\alpha)*$`file1`$+\alpha*$`file2`. A schematic of the two algorithms used can be seen in Figure 2.3.

[16]Image is a module within PIL which can be used for various image functions like scaling, rotating and merging. Documentation is available from http://www.pythonware.com/library/pil/handbook/image.htm.

[17]Python Imaging Library (PIL) is an extension to the Python programming language permitting image analysis, available from http://www.pythonware.com/products/pil/.

Note that we have used the `Image.blend` function which combines images pairwise, avoiding possible buffer overflow problems, thus necessitating the design of these algorithms. However the function could lead to loss of dynamic range in the final image, and it may be preferable to add all images together directly and divide by the number of images. This can introduce read/write buffer interpretation problems if we manually convert our pixel values to float numbers[18] and then convert back to an image. It is more robust to instead use Python's ImageMath module from PIL. A code to do this is found in Appendix A.4. The result of both Algorithm 2 and the ImageMath approach are in practice identical images.

Algorithm 1 is the more naïve of the two approaches. In the example given in Figure 2.3, we consider the case where we have 6 images we wish to combine. The simplest method of combining images is using the method of a "single–elimination tournament" (Horen and Riezman, 1984), where we have 2^n inputs, which are paired, and after n iterations of blending, we have a final image. This of course only works when our number of images is exactly a power of 2. If this is not the case, as in this example, we add "null images" to make the total up to the next power of 2. To achieve this we have created a blank image the same size as the cropped data images, but with all pixels having a value of 0, ie. a black rectangle. In the diagram, boxes 1–6 represent real data images, while boxes 7 and 8 represent blank images. Once we have 2^n images we proceed as in the single–elimination tournament, blending consecutive pairs with equal weighting ($\alpha = 1$) until we are left with a final image.
The primary disadvantage of this approach is that we may have a scenario where we have $2^n + \epsilon$ images, for some small (integer) value of ϵ, so that we need to add almost as many blank images as we have real images. Our blank images cannot simply be transparent, because we want to *blend* images, we must have defined

[18]Floats (rather than integers) typically have a larger number of bits available to store data, thus can be used to avoid overflow errors and loss of dynamic range.

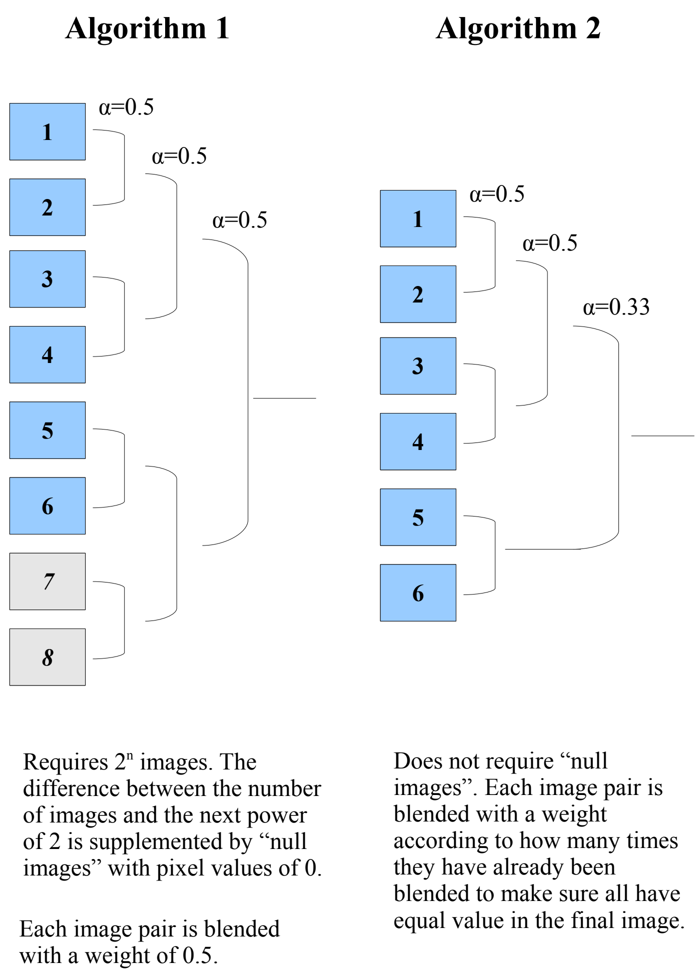

Figure 2.3: A schematic view of the algorithms used to combine cloud cover images.

pixel values. This leads to the question of what is a good blank image? We have chosen black, rather than white or 50% grey, however whichever blank we use will cause the final image to have its pixel values histogram biased towards that value. We could use a blank image of randomised pixels, and create a new set of random pixel values for every blank used. This may produce an unbiased (though potentially "noisier") image, but would also require more computational time to create the blanks. For this reason we also developed Algorithm 2.

Algorithm 2 may be considered the more quantitatively robust of the two algorithms, although it is a more complex approach (but equivalent to the direct addition method in Appendix A.4). In this scenario we again take the example of having 6 images to combine. This time we want to add all images equally into the final, without using any extra images. In this case, we consecutively add pairs, as in Algorithm 1, for as long as we can until we have a lone image or lone pair. We mark the number of blend iterations this occurred at, but continue iteratively blending the remaining images. Eventually we will have another lone blend, and we mark at what iteration this occurs. At this point, we blend the two "spare" images; however, they must not be weighted equally, else the first lone image or blend will carry more weight in the final image than the second lone blend. The weighting ratio for the two images is given by $weight\ \alpha = \dfrac{2^{it1}}{2^{it2} + 2^{it1}}$, where $it1$ is the iteration number on which the first lone image appeared, and $it2$ is the iteration number of the second lone image (which in practise is the current iteration). In this instance, the first lone pair appeared at iteration #1, while the second appeared at iteration #2. Thus $\alpha = \frac{2^1}{2^2+2^1} = \frac{2}{6} = \frac{1}{3}$. This makes intuitive sense in the example in the figure, as we are adding one pair to a blend of 2 pairs, the two pairs should carry twice the weighting of the one pair.

High-resolution Data

The high-resolution data were all well rectified and aligned, and covered a small enough geographic area that the first step of the low-resolution analysis was unnecessary. The summation method used was identical to that used for the previous image set, and so the code shown in Appendix A.3 is again relevant.

It readily became clear that the blended image using blanks was not helpful, as unless we know how many black images have been used and endeavour to compensate for them, these images are not quantitatively meaningful. The "no blanks" images, however, are a direct average of the images that made them, and as such their pixel values should be quantitatively meaningful.

While we did not proceed down this path for the low-resolution data, for this dataset we made a "total" cloud cover image (all images available) with the 2^{nd} algorithm which was used in the GIS analysis, but we also divided the data up into day and night images, and summer, winter, and "shoulder season" images (April and October), using scripts shown in Appendix A.5 (`daynight_im_sorter.py` and `seasonal_im_sorter.py`), and ran the relevant variations of the code in Appendix A.3 on each of those directories.

2.4 Results of Meteorological Analysis

Initially we present the results of the low resolution longer time-range data. Figure 2.4 shows the result of combining the data acquired from the online catalogue. These data are low resolution, with pixel sizes approximately 25×25km, which would be an acceptable resolution for at least qualitative results, however there are significant aliasing effects associated with the coastline overlay which in practise make the dataset virtually unusable. Figure 2.4 is not rescaled, the calculated values for each pixel are shown. Due to the very poor quality nature of this image, these data were not used further in the study, and only the shorter time range high-resolution data were used. It is thought that the poor quality of the otherwise reasonable resolution coastline is associated with the lossy JPEG compression used in the data files (Duncan, 2010), which in the combined image causes sufficient distortion to be unusable.

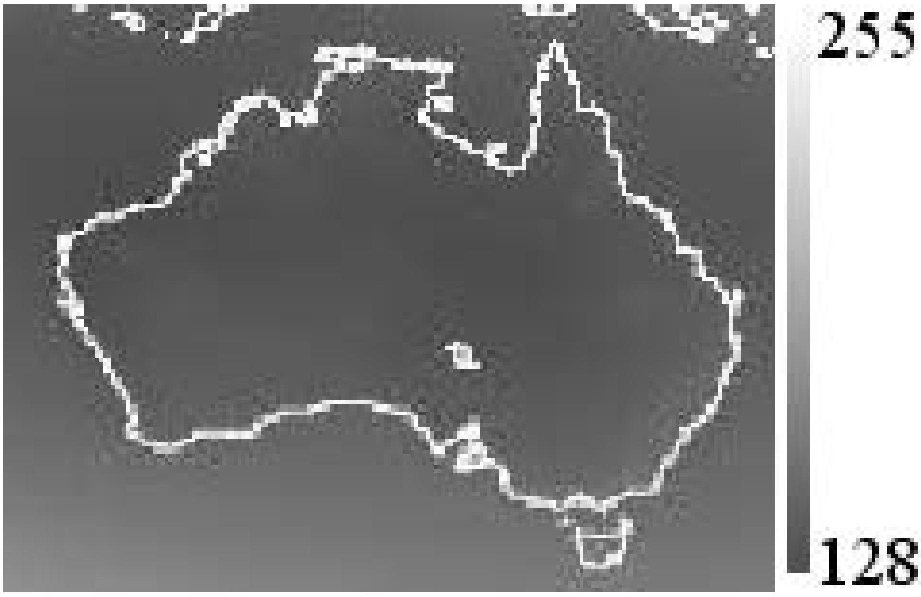

Figure 2.4: Low resolution total cloud cover over Australia in the period June 2004 to June 2008 showing pixel values.

In the remainder of this section we present the images produced as a result of the analysis described in Section 2.3.3. The images are greyscale 8–bit images with pixel values between 0 and 255. These values can be used quantitatively as in Chapter 3, however as every pixel has cloud in it at least some of the time, and as we have not applied thresholding to our data any changes due to land temperature have not been excluded, in fact all pixels hold values in a small range between approximately 80 and 120. Thus when displaying images here, we have manually rescaled the dynamic range of the image to match the histogram, so that the reader can better interpret where areas of high and low cloud coverage are. In practise the differences are not so pronounced. Without this adjustment, the colour range in the images is similar to that in Figure 2.4, where areas of high and low cloud cover are not easily distinguished.

For our GIS analysis we have chosen to work with the full set of high-resolution IR data, that is, the combined image which covers the full period for which we have data. Ideally we should have an integer number of years with equal days,

nights, summers and winters, but in practice we have approximately 18 months with approximately 1.5 summers and winters due to the time constraints of the project. This is not ideal, but we consider it best to work with as much data as possible in this instance. The rescaled version of this image is shown in Figure 2.5, where pixel value is linearly proportional to number of cloudy days. We are able to avoid the coastline image artefacts seen in Figure 2.4 with this data, as the raw data is obtained in GIF format, which is not a lossy compression format (unlike JPEG) (Duncan, 2010), so by creating the combined image as a bitmap (BMP) we are able to preserve the coastline in our data file which we use in analysis in Chapter 3. Image artefacts may still occur, however, in the presentation process, as the conversion to Portable Document Format (PDF) uses an intermediate JPEG stage. In Figure 2.5 we have mitigated this effect by creating the PDF image directly using Adobe™ software to create the PDF via ZIP compression rather than JPEG compression (Fleishman, 1998).
Note that this image is not that used for analysis, as it is both artificially created, and its dynamic range rescaled for reader accessibility. Consequently while the pixel values shown in the scales are real, they differ from image to image, and these values are not quantified in terms of observing time in Section 2.4.1. A false colour version of of Figure 2.5 showing only Australia is presented in Section 3.3 as Figure 3.2.

We have also made equivalent images showing day-time and night-time cloud cover, as seen in Figure 2.6. This image demonstrates the different response of the sensor to changing ground conditions between day and night. The actual cloud cover distribution in both images is very similar, however the colour of the continent changes. This is why "thresholding" was used by Coops et al. (1991) in their analysis to make sure they were sensitive only to cloud. The day image more clearly shows the cloud cover, but as we are interested in nights we choose to use the total image (shown in Figure 2.5) in our analysis. This is merely a demonstration of the different sensor responses according to time of day.

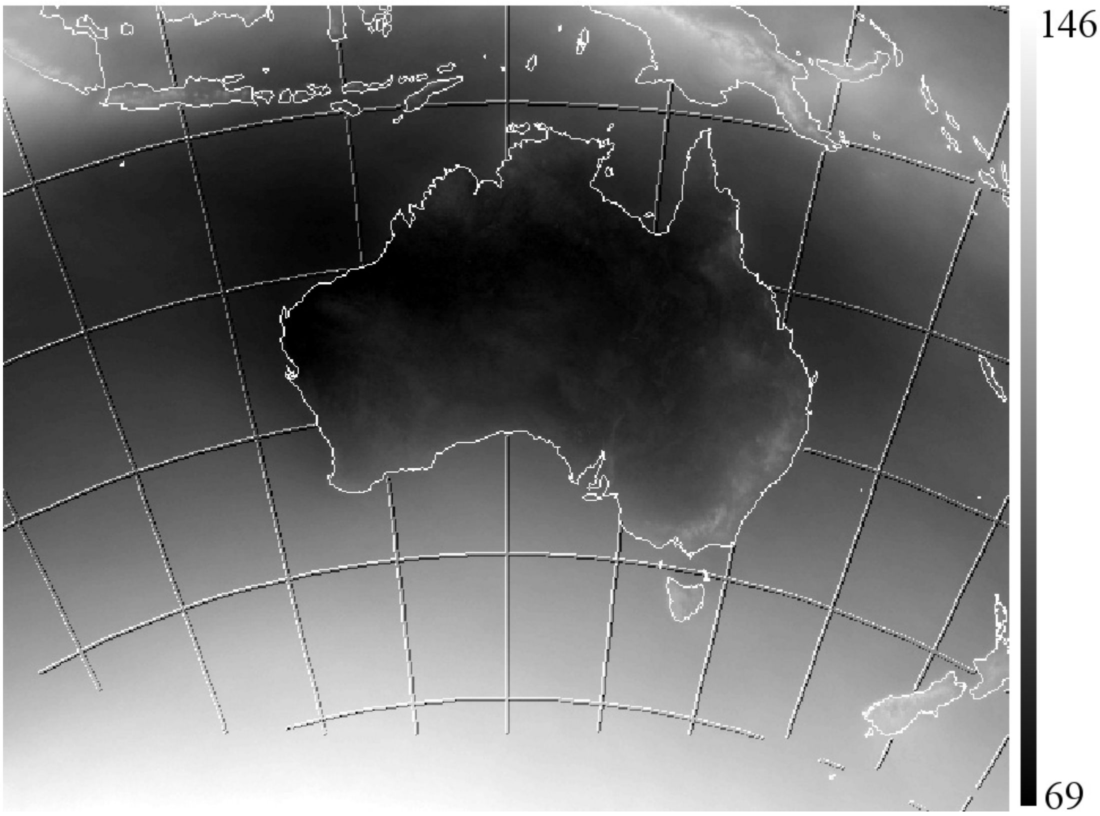

Figure 2.5: Total cloud cover over Australia in the period 11^{th} June 2008 to 22^{nd} January 2010 showing pixel values.

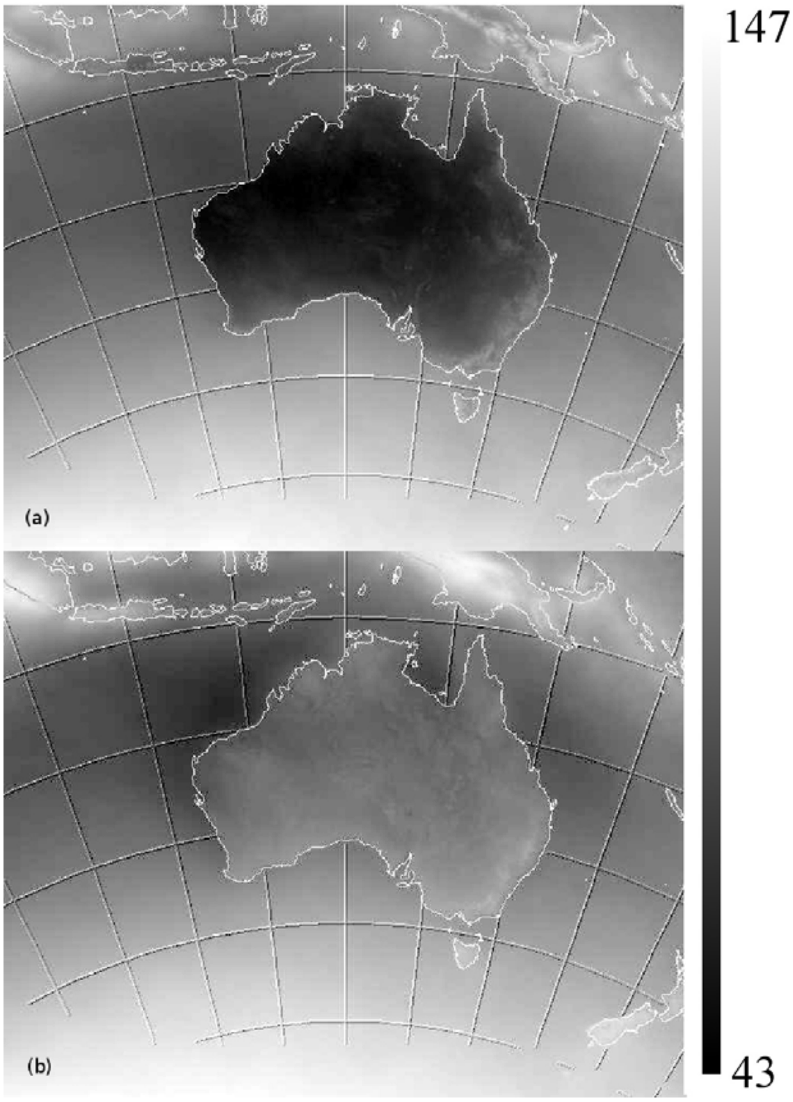

Figure 2.6: Total cloud cover over Australia during *(a)* Daytime and *(b)* Night-time in the period June 2008–January 2010 showing pixel values.

Finally we present an image showing continental cloud cover in the Summer months, the Winter months, and the "shoulder" months of April and October. The three images are not all composed of equal numbers of files for fairly evident reasons given our time–span (and that seasons are three months while our "shoulders" are two months), however Figure 2.7 demonstrates the seasonal variations across the continent, in that the Northern part of Australia experiences a cloudy and wet Summer while most of the remainder of the continent is predominantly cloud–free, and conversely the tropics are clear while the mid–latitudes are receiving winter rains. The shoulder seasons are the times between the Wet and Dry seasons in the tropics, and are the middle of Spring and Autumn in the lower latitudes.

2.4.1 Initial Conclusions Based on Cloud Cover Analysis

From inspection of Figure 2.5, we see that there are apparently promising regions of low cloud cover around Northwest Western Australia near the Hamersley Range in the Pilbara region, and extending inland toward the MacDonnell Ranges in the Northern Territory. There appears to some extent to be a correlation between altitude and cloud cover, which is not surprising as a mountain will tend to interrupt atmospheric air-flow and potentially trigger cloud formation. Nevertheless, it would appear from these analyses that suitably elevated sites in the Hamersley Range in W.A., such as Mount Bruce and Mount Meharry (both ~1200m elevation), may be good candidate sites, in agreement with the preliminary analysis by Glazebrook (1999) and the results (prior to site testing) of Coops et al. (1991), as well as an "intuitive guess" by Cole (2010) that a good site would be near a Tropic (Capricorn or Cancer), elevated, and relatively coastal. McInnes et al. (1974) also mention the potential suitability of Northern Western Australia, but dismiss the site due to its relatively low elevation on a global scale, and remoteness. Even so, they do mention the reputedly good skies in Western Australia.

We would also suggest based on Figure 2.5 that an appropriate site in the MacDonnell Ranges in the N.T. would be a good candidate site (with areas over 1000m elevation). With no particular knowledge of the area, a site in this low–cloud-cover area with maximal elevation for the area was selected, at $Latitude = -23.886^o, Longitude = 132.200^o$ (based on Google Earth™). Alice Springs, N.T., is considered to have very good astronomical seeing, despite being

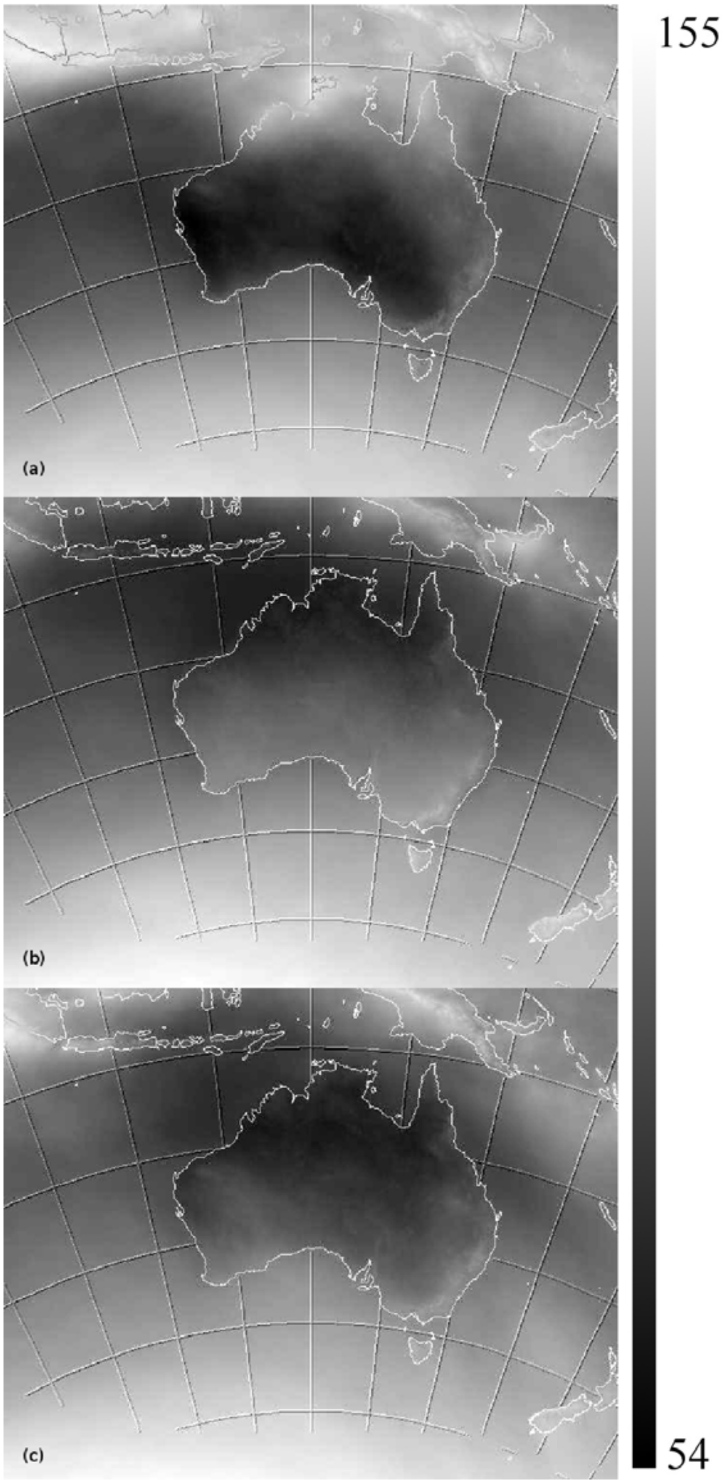

Figure 2.7: Total cloud cover over Australia during *(a)* Summer months, *(b)* Winter months and *(c)* April and October, in the period June 2008–January 2010 showing pixel values.

a long way inland and in a desert area with large diurnal temperature variations[19]. Coops et al. (1991) found two appropriate sites based on their cloud cover analysis, the Hamersley Range in W.A., and the northern end of the Flinders Ranges in South Australia (previously tested by Hogg (1965), and later tested by Wood et al. (1995) at an elevation of around 940m). While these sites are reputed to have very good seeing and very low cloud cover (as can be seen in the Summer (top) panel in Figure 2.7), our overall cloud summation does not appear to be in particular agreement with this suggestion. This may be due to our analysis using a rather temporally limited dataset, and our data may represent a particularly cloudy time in that region, and similarly Coops et al. (1991) data may have been sampled from a particularly dry or clear period. The 20 year gap between data sets may also be significant as climatic effects in the area could conceivably have changed in that period. Although we do not identify this area as being of apparently interest, with it's relatively low elevation (similar to the MacDonnell Ranges but lower than Siding Spring or the Hamersley Range), we will still include this site in our geographic analyses in Chapter 3.

Although the images shown in Figures 2.5, 2.6 and 2.7 have been manually adjusted to be meaningful to the reader, we are interested in the range of pixel values and how they relate to predicted available observing time. To attempt to quantify this we have selected 7 sites around Australia which we believe are identifiable and near enough to weather stations that we can assign a pixel value to that station. Note that the positional uncertainties may be quite large (up to 10s of kilometres) as this step was done by eye only. By looking at the historical data for each of the identified weather stations we can obtain an estimate for expected number of clear and cloudy days per annum, and thus relate pixel

[19]See, for example, "seeing" predictions for Alice Springs (or other towns) on this website http://www.meteoblue.com/en_US/point/forecast/tab/b/8/c/au/f/492, where seeing is regularly predicted to be around or below 1 arcsecond by their model (which being a model may not be entirely accurate but is a fair relative guide).

value to number of clear days. Note that a "clear" day as defined by the BoM is one with no cloud, and thus represents photometric astronomical observing conditions. A "cloudy" day can be considered a day on which observing would not be possible. These clear and cloudy day values for each identified site are shown in Table 2.1, and plotted in Figure 2.8. This indicates that it appears that there is an approximately linear correlation between pixel value and number of clear (or cloudy) days, with the rule derived from a linear regression of the data points given by

$$Clear\ days = -3.93 \times pixel\ value + 491.59. \tag{2.1}$$

This rule is clearly not physical, as pixel value approached 0 we would predict more than 1 year per year of clear days (perhaps due to the diurnal signal variations inaccurately raising the pixel values), however as an approximate guide it appears that we can say that for every reduction of one pixel value we gain approximately 4 observing nights per year. In the rescaled data displayed in Figure 2.5 there is slightly more than an order of magnitude more observing nights at the darkest pixel sites compared to the whitest pixels.

Station	**Pixel value**	**Clear days**	**Cloudy days**
Strathgordon (Tas)	118	16	211
Coonabarabran (NSW)	96	146	95
Alice Springs (NT)	76	200	63
Spring Creek (Vic)	103	80	160
Georgetown (Qld)	80	165	55
Arkaroola (SA)	81	182	62
Wittenoom (WA)	74	183	65

Table 2.1: Predicted number of clear and cloudy days per year at selected BoM sites.

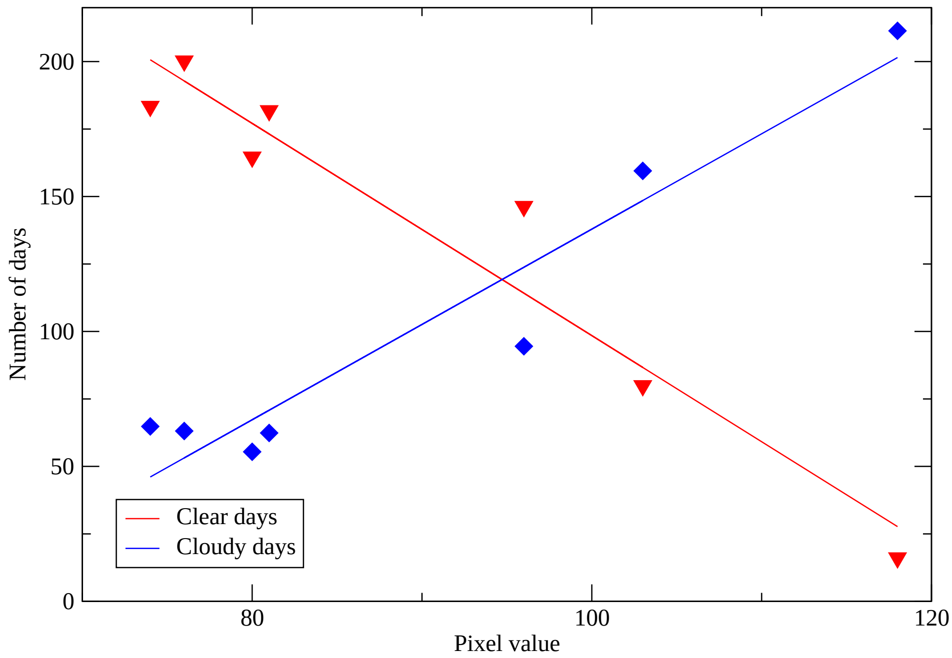

Figure 2.8: Plot of number of clear and cloudy days per year at selected BoM sites.

2.5 Conclusions from Meteorological Analysis

We have acquired both low-resolution extended time range, and high-resolution short time range infrared data taken by MTSAT–1R and downloaded from the Australian Government Bureau of Meteorology, as described in Section 2.3.2. Based on our analysis of the high-resolution data we have determined that the longer time range low-resolution data is not appropriate to our requirements (see results in Section 2.3.3 – *Low-resolution data*), however the higher resolution data analysis presented in Section 2.3.3 – *High-resolution data* appear to be much more quantitatively valuable. From Figure 2.5 we note the very low cloud cover over the North-West of Western Australia and extending inland into the Northern Territory, and based on the apparent scarcity of cloud coverage in these areas, we propose the mountainous regions in these areas as prospective telescope sites, for example Mt. Bruce (W.A.), Mt. Meharry (W.A.) and the MacDonnell Ranges (N.T.). We are also interested in the Flinders Ranges (S.A.) site proposed by Hogg (1965), Coops et al. (1991) and Wood et al. (1995), the Mt Singleton site proposed by Walsh (2004), and the site for the new University of Tasmania telescope on Bisdee Tier (Tas.) (Cole, 2010).

In Chapter 3 we will perform a geographic analysis across Australia to compare the six sites mentioned above to the sites currently hosting research-class telescopes: the Perth Observatory at Bickley (W.A.), the Gingin Observatory (W.A.), Canopus Hill (Tas.), Mount Stromlo (A.C.T.) (currently out of commission), and the Siding Spring Observatory (N.S.W.).

Chapter 3

Geographic Analysis

3.1 Background to Geographic Analysis

While in Chapter 2 we discussed the importance of meteorology in choosing a telescope site, there are other concerns, as described by Ardeberg (1983). The second and third sets of siting criteria listed by Ardeberg (1983) are geographic, being its altitude (ideally above atmospheric inversion layer), topography, temperature and temperature stability, air pollution, light pollution and seismic activity. We might naturally add to this list flood risk, land availability for the task, and environmental impact assessment concerns (ie. proximity to endangered flora or fauna and whether building such an instrument could affect these). We may also be interested in the fourth set of siting criteria suggested by Ardeberg (1983), which relate to convenience and costing – site accessibility and availability of water.

For these reasons it is desirable to carry out a geographic analysis of our proposed sites. However, in this study we intend to approach the question of geography in a similar fashion to the question of meteorology, that is, to perform a low-level analysis across the whole of Australia, and combine geographic factors with meteorological factors to describe suitabilities for not only our proposed sites, but anywhere in Australia. We may then modify which sites we propose as viable, and consider each one in detail. Costing is not factored into this study as it is considered a secondary concern to our key interests of observing time and astronomical seeing.

In this chapter we describe the process of geographic analysis in Section 3.1. In Section 3.2 we describe our geographic analysis combined with our meteorological results. Finally in Section 3.3 we describe the results of our analysis and comment on the proposed telescope sites, finally selecting those which appear viable from this analysis and upon which physical site testing should be performed.

3.1.1 Why do we need a Geographic Analysis?

As described above, a meteorological analysis is vital to siting a telescope, however it is not the only factor affecting the "goodness" of a telescope's location. Instead we also need to know that it will be sited in a place which is otherwise suitable for optical astronomy (or indeed astronomy at any other wavelength, as the principle of site selection methodology is the same).

In optical astronomy we are primarily interested in the "seeing" at a site – both typical seeing conditions, and best conditions (which should be sub-arcsecond). This is dependent not only on the cloud cover at a location, which more than anything simply indicates the number of observing hours available, but rather it also depends on the altitude of the site and the atmospheric conditions in the air column above and around the site. The atmosphere blocks many wavelengths of electromagnetic radiation from reaching the surface of the Earth, many of which are astronomically interesting (although harmful to life as we know it!). The higher in altitude we are, the less the atmosphere is able to block that radiation, and will disturb the propagation of that radiation less (as the radiation will not have to pass through as much of the atmosphere). The propagation effects on the radiation also depend on the turbulence of the atmosphere. As discussed in Section 2.2.3 and Figure 2.2, we want to have a good (stable) air column and laminar airflow over our site. This is not easy to determine without on–site tests, but we can certainly consider other geographic factors.

Finding the perfect site for a telescope in terms of having no cloud cover whatsoever will be of no value at all if the site is at sea level and has terrible seeing conditions, prone to flooding from upstream rainfall, and is in a military test firing range! Thus is is apparent that we need also to consider the geography of sites. This importance is noted by Ardeberg (1983), Graham et al. (2005), Mills et al. (1958), Sarazin et al. (2006) and Zhu et al. (2001). We need to find a location which is at a high altitude and has low horizons free of light pollution, is on land that could be acquired for the purposes of astronomical research, and is not likely to be prone to geological hazards. All of these requirements have a spatial component, and thus geographic analysis is appropriate. In this study, we focus on the combination of elevation with cloud cover using a Geographic Information System (GIS).

3.1.2 Geographic Information Systems

A Geographic Information System (GIS) is a set of tools that permit analysis of data with a spatial component. While the concept of geographic scientific analysis can be traced back to the 1850s, in the context of electronic data analysis, the existence of GIS software dates back to the 1970s and 80s when it came into more common use among researchers, local councils and the like, though typically in those days the software was interacted with through a text-based interface which ran on a Unix mainframe (Longley et al., 2005). Over the years GIS packages have evolved into more mainstream usage and applications. There are a number of commercial packages available such as ESRI ArcGIS[1] (the software used in this study, courtesy of Curtin University of Technology's Spatial Science group) and

[1]ArcGIS is the industry leader in GIS software, and part of a suite produced by ESRI, as described at http://www.esri.com/software/arcgis/index.html.

Intergraph GeoMedia[2]. Also available on some platforms are open source free GIS packages, the most widely used of which is GRASS[3]. A GIS consists of a number of aspects. It is a tool which can interpret geographic data of either a vector or raster nature, and supports database integration and querying tools. Operations can be performed on the data to extract further meaning than was apparent in the raw dataset, in particular by adding the geographic component. Finally, maps can be made with the GIS illustrating the information, and may assist in building the bridge between *data* and *information* to *knowledge* and *wisdom*, by presenting *evidence* that the user or reader may more readily interpret (Longley et al., 2005).

GIS analyses are used in a range of fields, including Environmental Sciences, local and state Governments, Health Sciences, Transport and Logistics, Demography and Land usage. The range of applications of GIS and the science associated with Geographic Information is vast, and extends even to fields such as Computing and company location strategies (Longley et al., 2005). In this circumstance we are interested in remotely sensed meteorological data, which of course is spatial in nature, and what information can be obtained by linking this data to other datasets with spatial information that is important to us, in particular, a Digital Elevation Model (DEM). In many ways this is not a very deep GIS analysis, as the software is capable of far more powerful data manipulation. One could conceivably wish to perform in this context by investigating the locations of all optical or radio telescopes in Australia and whether they are well distributed over area, altitude, distance from artificial light pollution (towns, mines etc.), and so forth. While such a study is irrelevant to, and thus beyond the scope of, the question at hand, for interest's sake, a map showing the distribution of research-sized optical and radio telescopes is presented in Appendix B.

[2]GeoMedia is the GIS arm of the larger company Intergraph, with information available from http://www.intergraph.com/sgi/products/productFamily.aspx?family=10.

[3]GRASS, the Geographic Resources Analysis Support System which runs under a range of platforms and is the leading open source GIS suite, described at http://grass.osgeo.org/.

3.1.3 Multi-Criteria Decision Analysis

Geographic Information Systems is a large research field as well as having many applications in a range of industries, as described by Longley et al. (2005). One particular and very important aspect of GIS is the analysis method and science of Multi-Criteria Decision Analysis (MCDA) (Figueira et al., 2006; J.MCDA, 2010; Longley et al., 2005; Malczewski, 1999). MCDA is a process by which a number of parameters affecting the goodness of a location for a task are identified ("multi-criteria"), their relative importance is determined using some decision metric and whether each variable is Boolean (for example "not in a lake") or "continuous" (for example "as close to a road as possible") in nature. The variables are then combined by some algorithm according to the task and a final value for suitability is obtained. Each variable needs to be "normalised" so that they are unitless and can thus be combined (we cannot compare cost with distance, but we can compare fractional cost with fractional distance). If Boolean, the suitability may be a vector layer covering some areas, while if raster, the suitability may be a value between 0 and 1, or 0% and 100% covering all locations, or a combination of the two (e.g. a continuous suitability value but only in areas defined as being permissible).

A common algorithm for combining continuous data is the weighted sum approach, that is

$$suitability = \sum_{i=1}^{n} weight_i \times criteria_i, \tag{3.1}$$

where each criteria is multiplied by its weight, where each weight $\epsilon(0,1)$ and $\sum w_i = 1$.

The weights are obtained via a decision making metric (Clemen, 1996; Figueira et al., 2006; Maxwell, 2008) that allows the user to determine which of the variables are important and their relative importance in the system. In some cases the values of w_i may not be known or readily derived, in which case it may be necessary to compute the suitability for a number of weighting schemes and compare their outputs. It may be possible to use independent data to justify the best choice of weightings. Alternatively, in the case of competitive values, it may be instructive to perform the analysis using the weightings of each party, and as a neutral bystander, to assist in determining the best approach to solving the problem[4]. In the case of a decision involving only Boolean data, the suitability mask is simply computed as

$$suitability = \prod_{i=1}^{n} criteria_i. \tag{3.2}$$

Therefore a general suitability involving both raster (continuous) and vector (Boolean) criteria, might for example be given by the rule

$$suitability = \prod_{a=1}^{k} criteria_a \times \sum_{b=1}^{l} (weight_b \times criteria_b), \tag{3.3}$$

where we are working with k Boolean suitability criteria and l continuous suitability criteria. In this case the output layer will be a raster layer of suitability values which may be clipped to the vector suitability area.

In this study we will be using the simple raster suitability given in Equation 3.1. We have implicit Boolean cropping (Equation 3.3), in that we are only interested in the places for which all combined datasets contain real values. That is, we only compute suitability values on land, where we have a defined value for elevation.

3.2 Using Multi-Criteria Decision Analysis in a Geographic Information System to Choose Telescope Sites

In order to perform a geographic analysis to find an appropriate site for a telescope, it is reasonable to use MCDA. The major focus of this study will be in

[4]For example, we may have an area which is ear-marked to be listed as a National Park, but which contains some significant mineral deposits in which a mining company has an interest. The importance (weighting) of various factors assigned by each party will differ, so it is hard to objectively weight the importance of each variable, in which case further analyses and criterion weightings will be required, maybe extra criteria will need to be added.

finding general regions in which telescope siting is likely to be productive, that is, we will not focus in detail on the lower-level criteria.
We consider the very important aspects of a telescope site to be its **elevation** and its rate of **cloud cover** (from the meteorological analysis). These two criteria are the primary criteria used to derive suitabilities across the country in Section 3.3. Lower-level criteria include proximity to roads, distance from townships and other sources of light pollution (such a mines), availability of land for this use (not under native title claims or in other excluded zones), potential risk from floods, bushfires, earthquakes, cyclones and so forth, and suitability of the land for this infrastructure. None of these concerns are covered in our initial analysis, though we will discuss them for each prospective site. Also of concern are temperature profiles and atmospheric turbulence, but these data can only be accurately obtained through on-site monitoring, which has not been performed in this study, but possible methods are described in Chapter 4.

Geographic analyses of potential telescope sites have been performed for other instruments (Graham et al., 2005; Sarazin et al., 2006; Zhu et al., 2001) such as the European Extremely Large Telescope (E-ELT), which as described by Sarazin et al. (2006) has even had its own GIS package written for the task, FriOWL. This software is designed to take into account a number of atmospheric effects in conjunction with land elevation in order to identify potential sites for very large telescopes, and as such, works with long time-range data but at relatively low resolutions. Because we are working under the constraint that we are looking to site a telescope *within Australia*, the capabilities of this software have not been considered relevant to this project, and we have instead opted to use ArcGIS v9.3 for our analysis.

For our primary analysis, we are interested in the rate of cloud cover, as this is analogous to available observing time as discussed in the introduction to Chapter

2. We are also interested in the astronomical "seeing" available at the site. This is related to the thickness, clarity and turbulence of the atmosphere over the site. However, to a low order, we can consider elevation (altitude above sea level) to be a proxy for seeing conditions, as greater elevation means less atmosphere for light to pass through and potentially different and more stable air columns than at sea level. In a densely populated country we would also be concerned about proximity to populations centres, however Australia is a sparsely populated country, and the vast majority of the population lives in coastal regions, meaning that most mountainous regions have particularly low population densities, and thus we would not expect significant light pollution problems in these areas (barring any adjacent mines, which may cause light pollution problems).

3.2.1 Sources of Data

The data used in this analysis is that created in Section 2.4, the high–resolution averaged cloud cover over Australia between June 2008 and January 2010, shown in Figure 2.5. This map is derived from data provided by the Bureau of Meteorology, as described in Chapter 2.

All geographic data used in this study were obtained from Geoscience Australia's (GA) free data downloads[5]. Importantly, the Digital Elevation Model (DEM) used was the 9 arcsecond DEM[6], which relates to a grid size of roughly 250m square. This is significantly higher resolution than the cloud cover data which has cell sizes of approximately 25km square.

Further datasets were downloaded from GA as required, including earthquakes (as an indicator of earthquake risk), local government information including land use and political boundaries (including country and state outlines), and datasets

[5]Geoscience Australia (GA), Free Data Downloads, ©Commonwealth of Australia, https://www.ga.gov.au/products/.

[6]GA 9 second DEM (DEM–9S) v3 information can be found at http://www.ga.gov.au/bin/htsqr?file=/oracle/geomet/geomet2.htsqr&datasetno=11541.

for each map area including roads, airfields and so on. Some data were manually created, such as the layer showing present and proposed telescope locations, which were determined from known locations from information about existing telescopes, or determined to an approximation using Google Earth™ and manually entered into a data file of telescope locations which was saved as a comma separated value (`.csv`) file for importing into ArcGIS.

3.2.2 MCDA Method

In order to combine "layers" in our GIS, we need to be adding like quantities together. It is not logical to compare, for instance, a distance in km with a price in *$*. However if we can normalise our criteria we are able to compare them, as both variables will then have a rating between 0 and 1. It is important to note at this point that this study is predicated on wishing to build a telescope *in Australia*, and thus this normalisation to create suitabilities only applies within Australia. This allows for relative comparison of the goodness of sites over the region considered, but we cannot immediately compare suitabilities calculated in this analysis to suitability values for sites in other parts of the world, we would first need to rescale or reweight our values to correct for our lower mountains, and cloud cover which may be higher than in other parts of the world. Sites in Australia will be of a lower absolute suitability than sites in, for example, Chilé.

The DEM can be re–sampled to 10 category values of altitude, selected to best sample the histogram, but for actual MCDA, in this instance it is better to use the actual altitude value, scaled so that the altitude suitability is given by

$$altitude_{suit} = elevation \div Max(elevation). \tag{3.4}$$

We define this criterion's suitability thus on the basis that higher is always better, even though it is possible that in the desert, any altitude greater than 500m may be sufficient to escape ground effects (depending on diurnal convection currents in the air column), while in mountainous areas like the South East of the Australian continent, elevations over at least 800m are likely to be required.

When we display our cloud cover data we have re-sampled it – stretched to "equalise histogram", which best displays fine structure in small changes in cloud cover values for the most cloud-free areas. For calculation, however, the raw values are used. We wish to normalise such that areas of low cloud cover have high suitability and areas of high cloud cover have low suitability, so we reverse our suitabilities by subtracting from 1.
To scale the cloud cover data to it's criterion suitability, we might intuitively expect that as the data takes values between 0 and 255, that the rule

$$cloud_{suit} = 1 - (PixelValue(cloud) \div 255) \tag{3.5}$$

would produce the appropriate dataset. However while this rule will indeed normalise the data, the effective dynamic range of the data remains very small, and changes in pixel value are hard to detect by eye (which is important, as after all we wish to produce maps of the suitability). Instead we need to also rescale the dataset. Inspection of the histogram of the layer indicates that virtually all "real" data points (excluding the coastline and globe lines running over the ocean) take pixel values between approximately 67 (minimal cloud cover) and 127 (maximal cloud cover). That is, despite the layer having 256 possible values, only 60 of these are actively used. Thus we can linearly rescale and normalise this layer (given the roughly linear trend seen in Figure 2.8) according to

$$cloud_{suit} = 1 - ([PixelValue(cloud) - 67] \div (127 - 67)). \tag{3.6}$$

We now have criterion suitability layers for our two key criteria – elevation and cloud cover rate, which can in principle now be combined together using Equation 3.1. First though we need to determine what the weighting of each criterion should be. As there is no clear distinction between which is more important, high elevation or low cloud cover, but rather we wish to optimise the two, the best approach was determined to be to calculate suitabilities for a number of combinations of criteria weightings, and discuss the implications of each (in Section 3.3). The reason this occurs is that not all types of astronomy have the same requirements in terms of observing time and atmospheric conditions, and so in this project, where we are not aiming to site *a particular telescope*, but rather we wish to consider what types of research telescopes could be located in Australia, each suitability metric will favour a different type of instrument or observing style.

3.3 Results of MCDA in ArcGIS

In this section we present the results of our GIS analysis. We have obtained the 9 arcsecond DEM from Geoscience Australia, and this is shown in Figure 3.1. The figure is coloured to 3 standard deviations, meaning that we emphasise the near–mean detail and only set the colour–scale to its maximum or minimum value when we are significantly far from the mean value. The Great Dividing Range which runs along Australia's East coast is highly visible, as are the moderately elevated regions in the Northern Territory and Western Australia. Lake Eyre, an occasional inland sea in South Australia, is dominant with its very low elevation. This map is included to give the reader a feel for what the elevation dataset looks like before it is combined with the meteorological data. Just as we drew conclusions from the cloud cover map in Figure 2.5, so we can say that intuitively, if we are interested in elevation, we will primarily look for sites along the Great Dividing Range, and then also consider parts of Tasmania, Queensland, South Australia, and the inland regions of the Northern Territory and Northwest Western Australia.

We now wish to optimise our telescope location by combining the meteorological data with the elevation data. In Section 3.2.2 we discussed rescaling our cloud cover data to the range (0, 1) to show best and worst cloudiness locations not in an absolute scale, but to a scale representing goodness within Australia, to

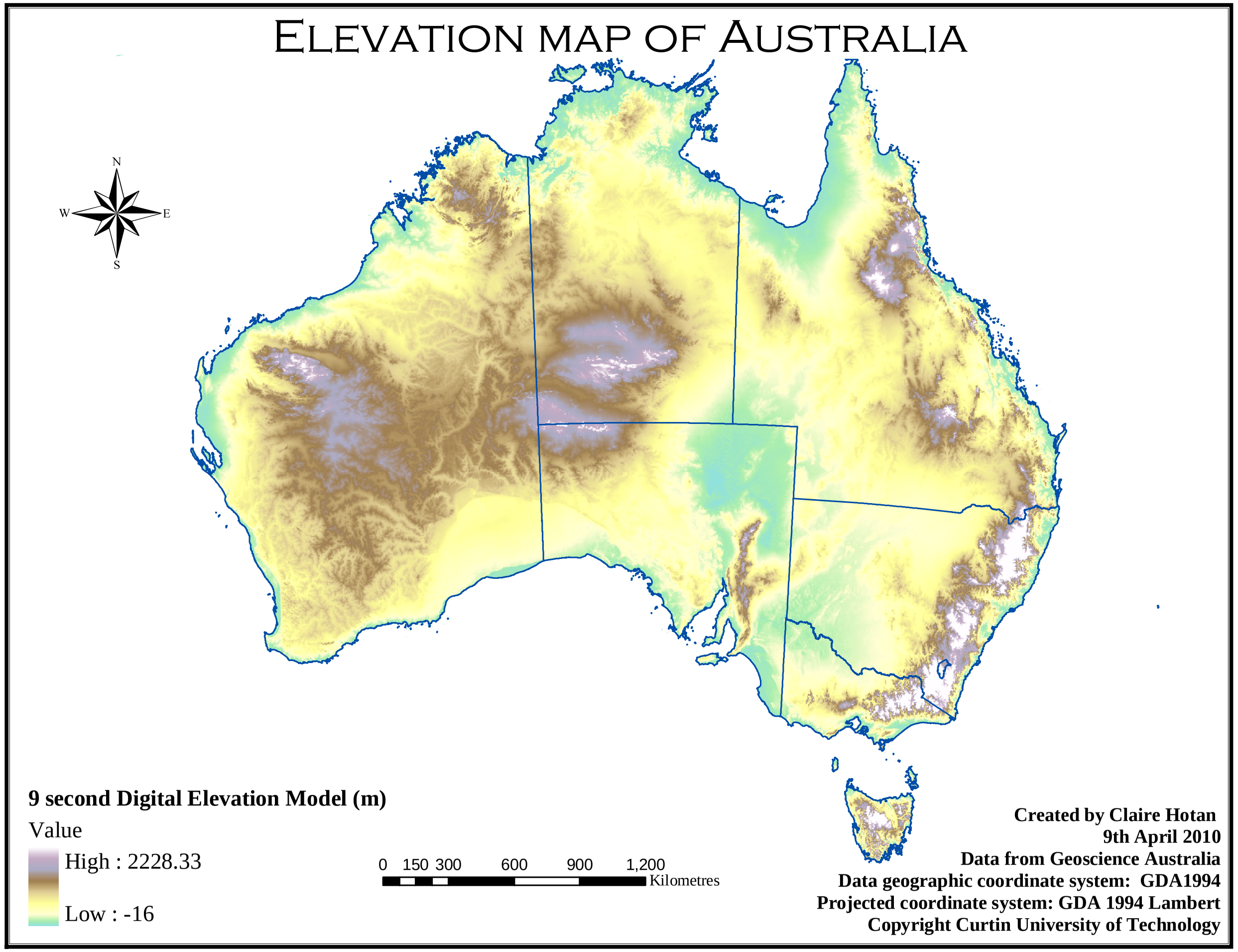

Figure 3.1: Map showing elevation across Australia at ~250m resolution.

make the lowest cloud cover site have values near 1 and the highest cloud cover sites have values near 0, even though neither site would have absolutely no, nor continuous, cloud cover. The result of this rescaling given by Equation 3.6 is shown in Figure 3.2. Note that we have resampled the layer to have the same resolution as the DEM. This resolution is "false" in the sense that our data is only sensitive over each low-resolution cell, but we have in a sense "interpolated" in order to crop the cloud cover data accurately to the DEM, producing an apparent resolution of less than 30km. To understand the cloud cover rate values, consider the data shown in Table 2.1 and Figure 2.8.

We now combine these two layers using the MCDA method described in Sections 3.1.3 and 3.2. Prior to weighting the two layers and performing a raster addition, we may simply plot the two layers on the same map, to help us visualise what we are looking at. Figure 3.3 shows the cloud cover image prior to re-scaling and cropping to the continental extent (which indicates an area of very low cloud cover off the Northwest coast of Western Australia), transparently overlaid on the digital elevation model, so that we can to some extent see the correlation between latitude and cloud cover, but also mountains and cloud cover (rather unfortunately in terms of this study!).

When we combine the two layers shown in Figures 3.1 and 3.2 we will use the Equation 3.1. We will consider 3 cases:

1.	Equal weightings	$w_{DEM} = 0.5$	$w_{cloud} = 0.5$
2.	Twice Elevation	$w_{DEM} = 0.667$	$w_{cloud} = 0.333$
3.	10% cloud	$w_{DEM} = 0.9$	$w_{cloud} = 0.1$

Each of these cases represents a different set of conditions which will be appropriate to a different type of telescope or observing. We always want elevation to be a key factor, as atmospheric clarity will always be important.

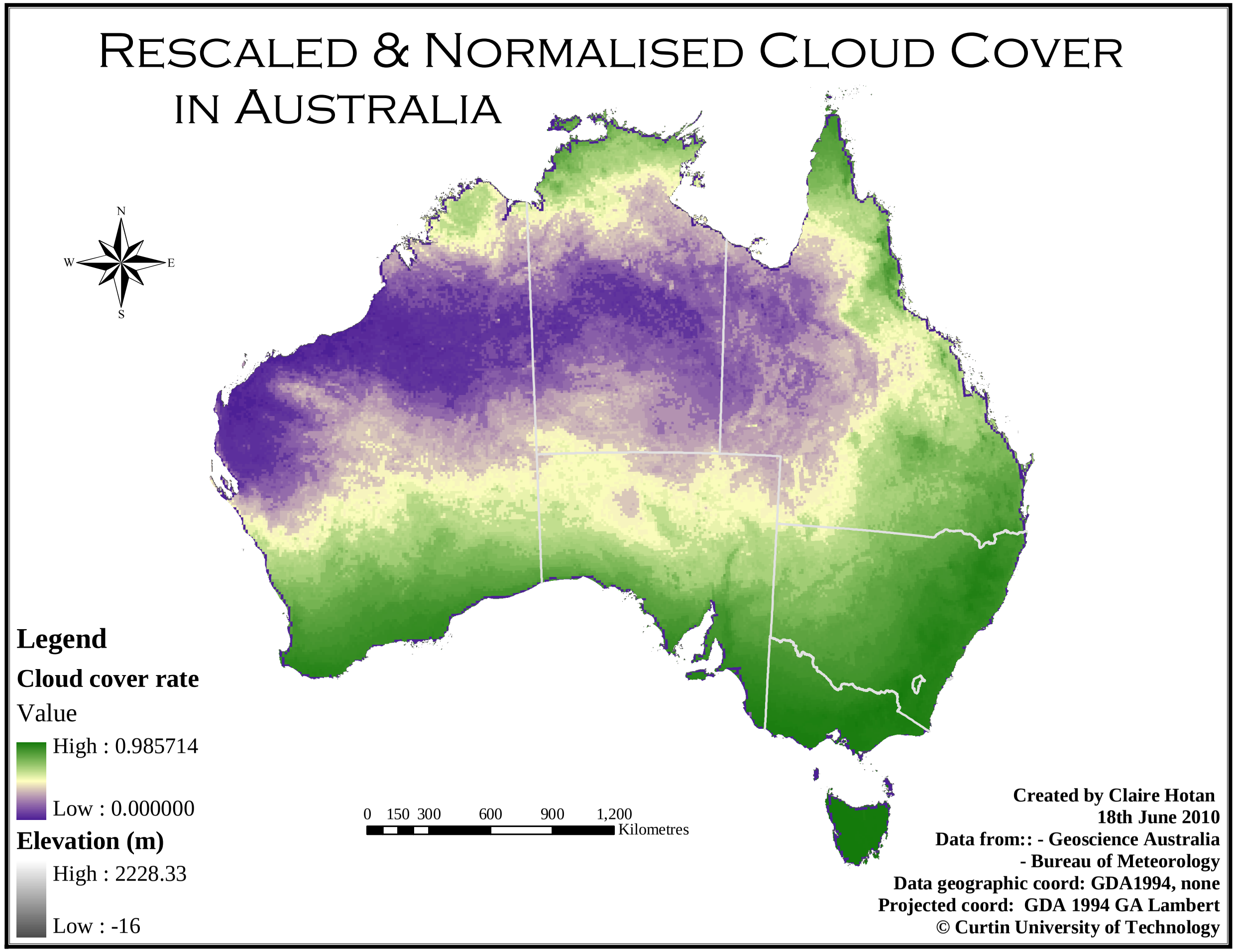

Figure 3.2: Map showing relative cloud cover across Australia at false ~10km resolution.

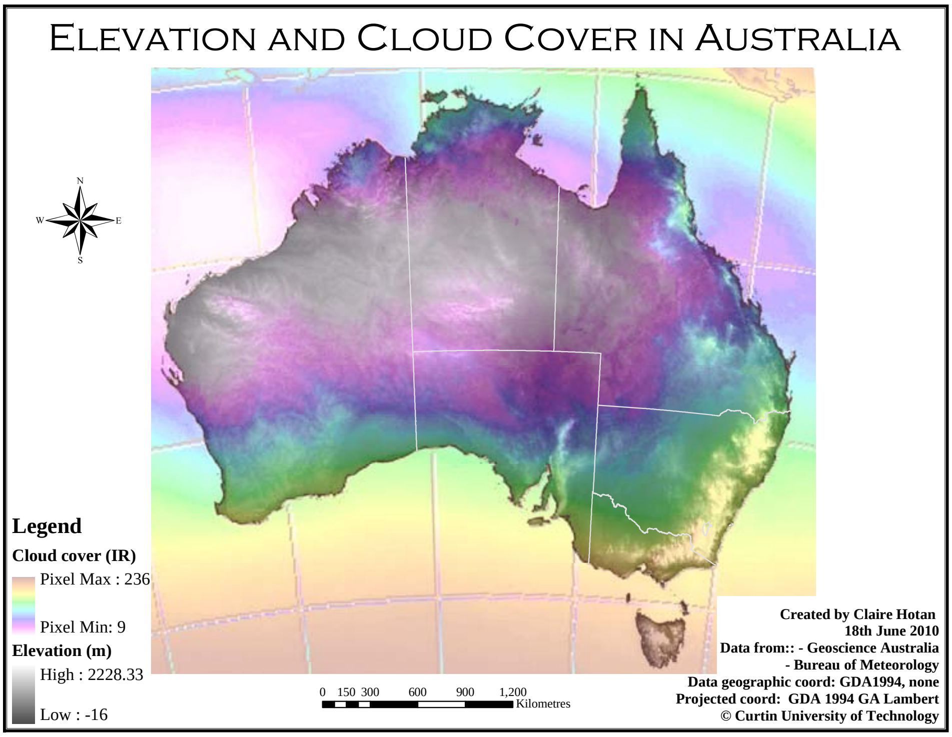

Figure 3.3: Map showing cloud cover and the elevation of Australia.

3.3.1 Case 1: Equal Weightings

Here we consider low cloud cover and high elevation to be equally important. This is a fairly intuitive choice for a first trial, and represents the case for which low cloud cover is given the greatest weighting. Such a suitability metric would be appropriate for a telescope on which we primarily value having a lot of observing time, with goodness of atmosphere of no greater importance than the time we can spend observing. This allows us to potentially observe objects with very long integration times, or to search for many objects as frequently as possible. This metric would be suitable for siting a telescope whose primary purpose is transient follow–up work and Near Earth Object (NEO) detection and tracking. These do not require very large telescopes (typically they currently range in size up to a maximum of around 1m). Any application in photometry may also be well sited by this metric. The transient follow–up capabilities of a telescope with a high probability of good observing conditions is particularly important if we consider furthermore wishing to site our telescope in the general vicinity of leading radio astronomy instruments such as the MWA (Lonsdale et al., 2009), ASKAP (Johnston et al., 2008) or the SKA (Dewdney et al., 2009) (should it be built in Australia).

Figure 3.4 shows the result of combining the data in Figures 3.1 and 3.2 by adding them together (when both are scaled to between 0 and 1 as described in Section 3.2.2) and multiplying each by 0.5, that is,

$$suitability = 0.5 \times DEM_{scaled} + 0.5 \times (1 - cloud\ rate). \tag{3.7}$$

This map also shows the locations of existing telescopes and proposed research telescopes as listed in Section 2.5, to give the reader a feel for the location of and approximate suitability of each location under this metric.

3.3.2 Case 2: Twice Elevation

In this case we consider the elevation to be twice as important as low cloud cover. However, this still places a lot of importance on low cloud cover, and hence long observing times. This metric would perhaps be appropriate for a telescope in which we require fairly good seeing, and much observing time. The applications for such a telescope would be similar to those in Case 1, maybe extending into larger aperture telescopes which we may use for spectroscopy, as we would expect long integration times to be possible combined with fairly good atmospheric conditions. Extensions to work done at the Australian Astronomical Observatory in New South Wales may be possible with such a telescope, such as surveys like 6dF (Jones et al., 2004) and WiggleZ (Drinkwater et al., 2010). Depending on the actual seeing conditions at the site, a telescope built for this purpose may have an aperture of around 4m, similar to the AAO (Anglo–Australian Observatory, 2006), or even larger, up to perhaps order 8m.

Figure 3.5 shows the result of combining the data in figures 3.1 and 3.2 by adding them with a weighting of ~0.667 on the DEM and ~0.333 on the cloud cover rate,

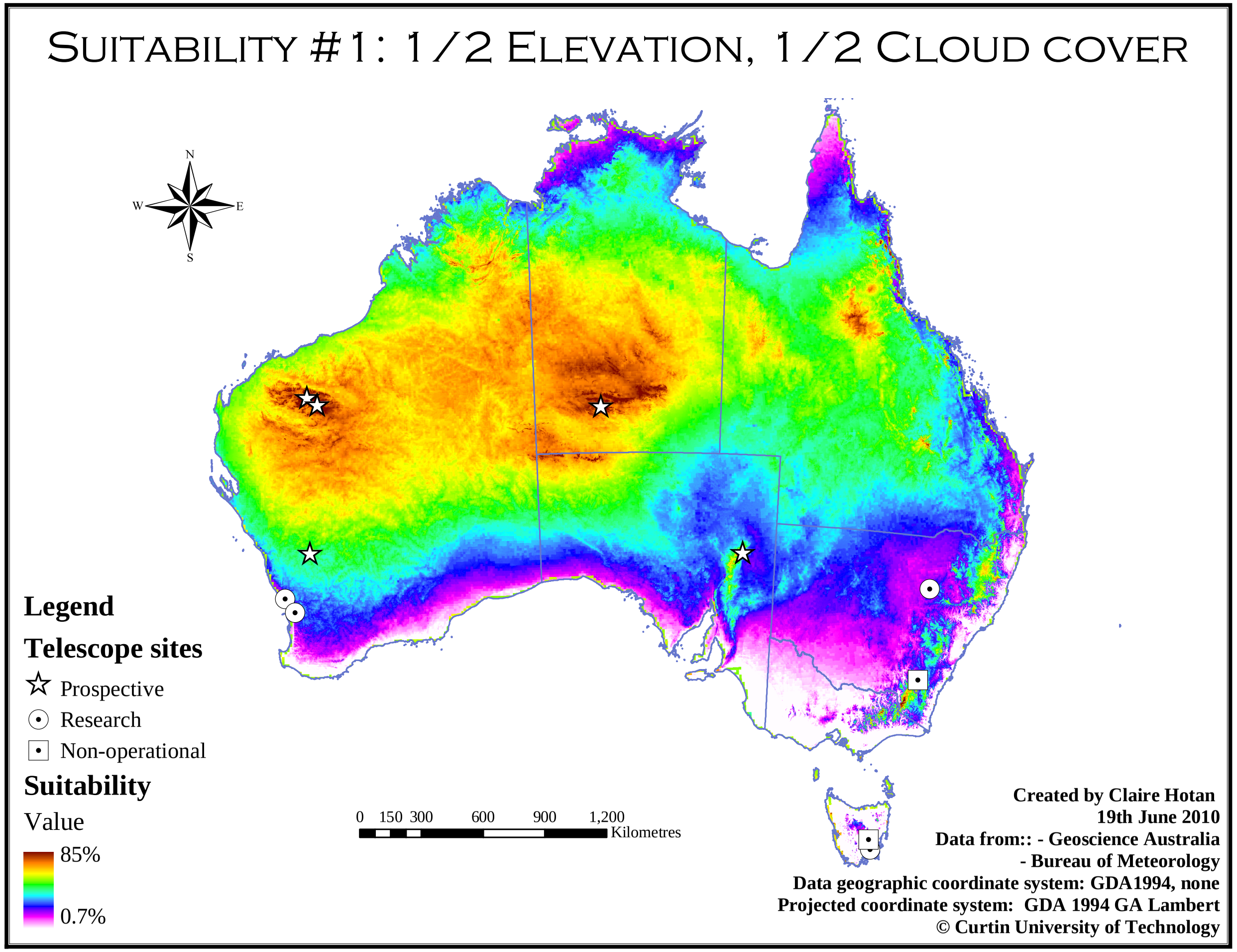

Figure 3.4: Map showing suitability values across Australia for an “Equal weightings” metric.

that is,

$$suitability = 0.667 \times DEM_{scaled} + 0.333 \times (1 - cloud\ rate). \quad (3.8)$$

As with Figure 3.4, this map also shows the locations of existing telescopes and proposed research telescopes as listed in Section 2.5, to give the reader a feel for the location of and approximate suitability of each location under this metric.

3.3.3 Case 3: 10% Cloud Cover

In this section we consider looking for a site where we are predominantly concerned with elevation, with low cloud cover being a rather secondary factor. Such a metric is useful for siting telescopes where astronomical seeing is of prime importance, but we are willing to accept non-ideal cloud cover statistics to achieve this. Such a site would allow very good imaging, at least of objects bright enough to be detected without very long integration times. If the elevation of the site is sufficiently high, the observing bandwidth of the telescope may be able to be extended into the near- and mid- infrared (IR) regimes, which at sea level and lower altitudes is absorbed at most wavelengths by the atmosphere. Unfortunately there are few high mountains in Australia, and none are sufficiently high that one would seriously consider building an infrared telescope, but we may be able to build an optical telescope which has sensitivity in some IR wave bands (for example, the ANU Mount Stromlo 2.3m telescope at Siding Spring has Near IR detectors, and as such some work is clearly possible in Australia). If IR astronomy is of particular interest then better results can be gained by going to high elevations in Chilé or even Antarctica, but we may be able to do some limited work in this area even in Australia if we find a good enough site. Such a telescope would not necessarily need to have a particularly large aperture.

Figure 3.6 shows the result of combining the data in figures 3.1 and 3.2 by adding them with a weighting of 90% on the DEM and 10% on cloud cover rate, that is,

$$suitability = 0.9 \times DEM_{scaled} + 0.1 \times (1 - cloud\ rate). \quad (3.9)$$

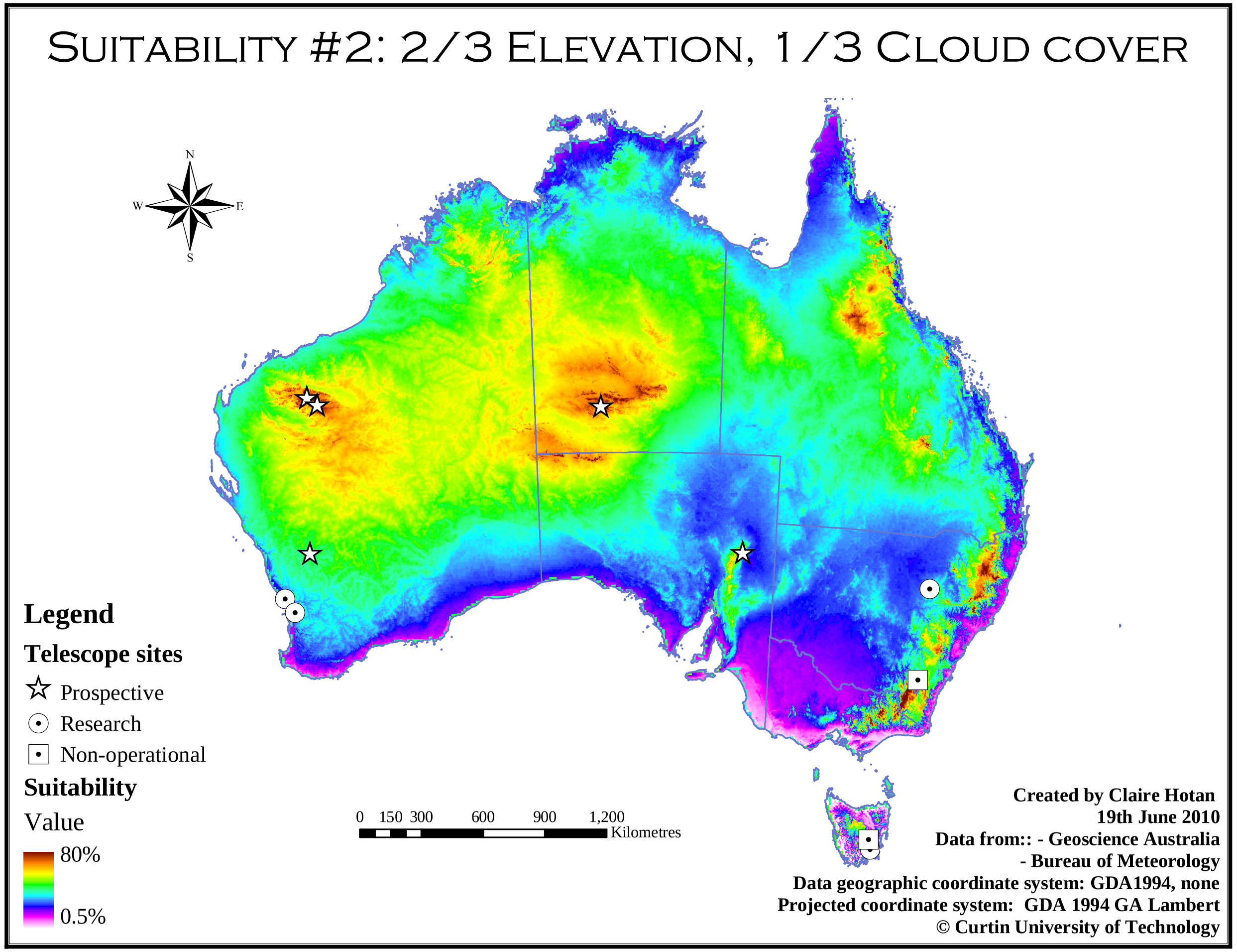

Figure 3.5: Map showing suitability values across Australia for a “Two times elevation” metric.

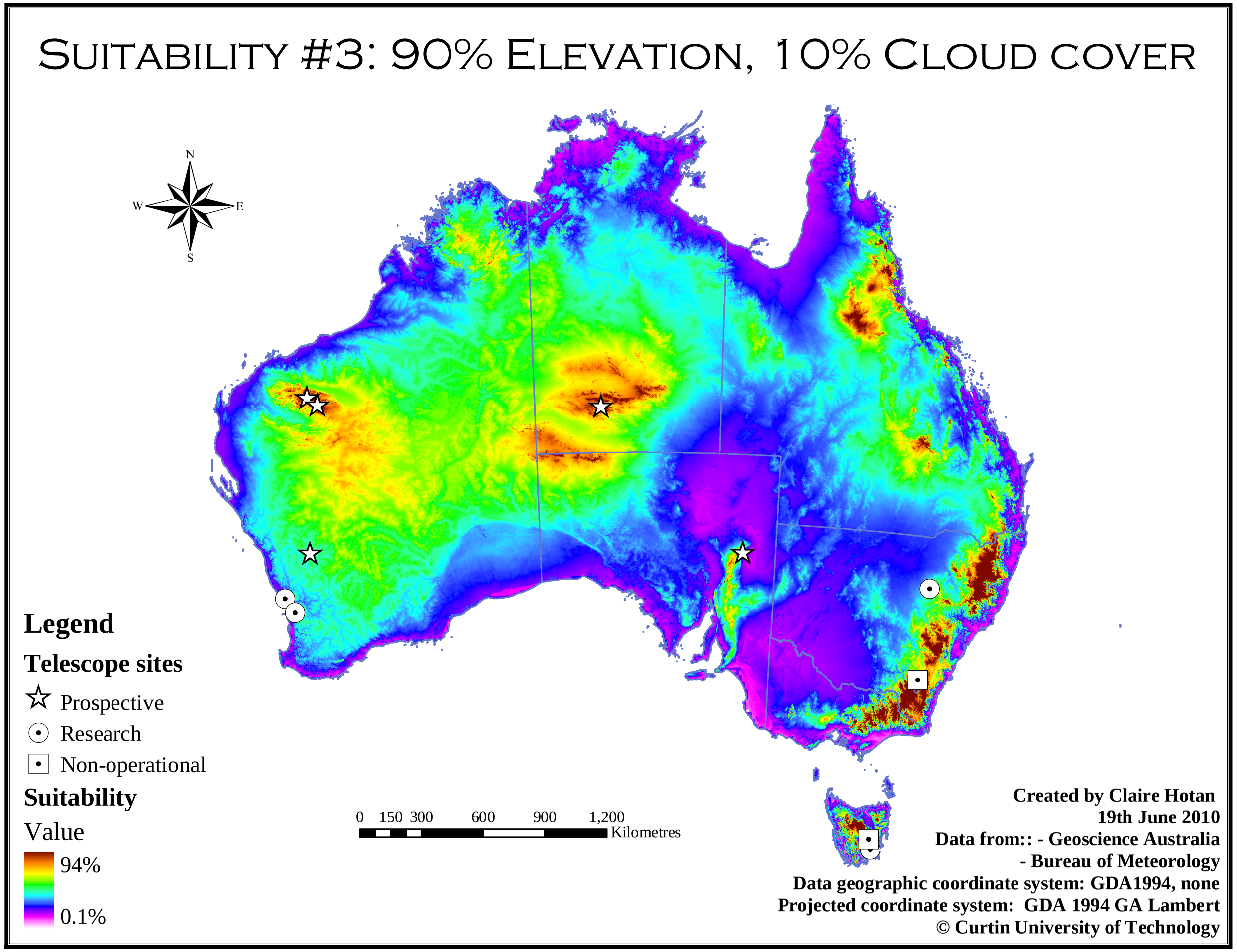

Figure 3.6: Map showing suitability values across Australia for a "10% cloud cover" metric.

As in the previous two figures, this map also shows the locations of existing telescopes and proposed research telescopes as listed in Section 2.5, to assist in understanding the approximate suitability of each location under this metric.

3.3.4 Boolean Metric Results

The previous three images, Figures 3.4, 3.5 and 3.6 show the value of their metrics across Australia, so that we may gauge the goodness of any given site. Instead suppose we are interested just in knowing how much of Australia is "suitable" under each metric, or where the most suitable areas of each metric are.

To do this, we apply a Boolean condition to our metrics – that they should have value 1 if their suitability is greater than 50%, and 0 if their suitability is less than 50%. 50% is an arbitrary cut-off chosen to demonstrate the areas made available under each metric clearly. However it is perhaps worth noting at this point that a 100% suitability is virtually impossible, as to achieve this, we would require that the highest elevation in Australia be associated with the very lowest cloud cover. In practice this is not the case, in fact we see in all the three figures presented above that the highest suitabilities are significantly less than 100%. Thus looking for areas of better than 50% seems reasonable. Note that this does **not** mean 50% good observing time, it means 50% as good as the theoretical ideal site in Australia.

In Figures 3.7, 3.8 and 3.9 we present maps equivalent to those above, using the three metrics described, but this time showing regions where the calculated suitability value is more than 0.5.

3.4 Discussion of MCDA Results

Let us start by making some comments on the images in Section 3.3. The Boolean suitability maps presented in Figures 3.7, 3.8 and 3.9 show the areas which we may classify as areas in which to consider a telescope under each metric. Note

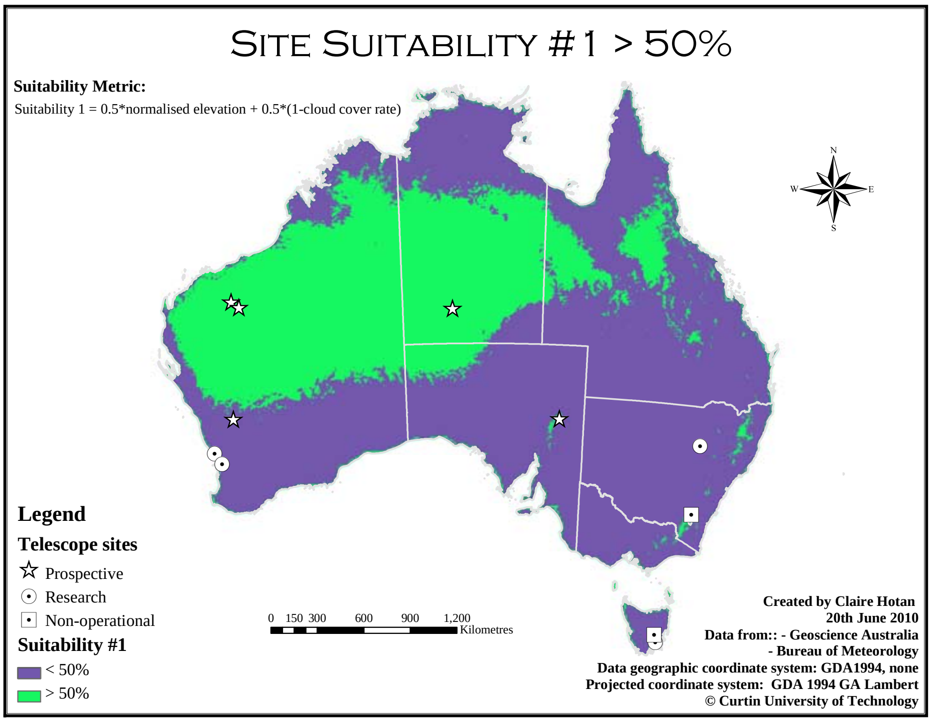

Figure 3.7: Map showing areas of Australia with metric #1 value > 0.5.

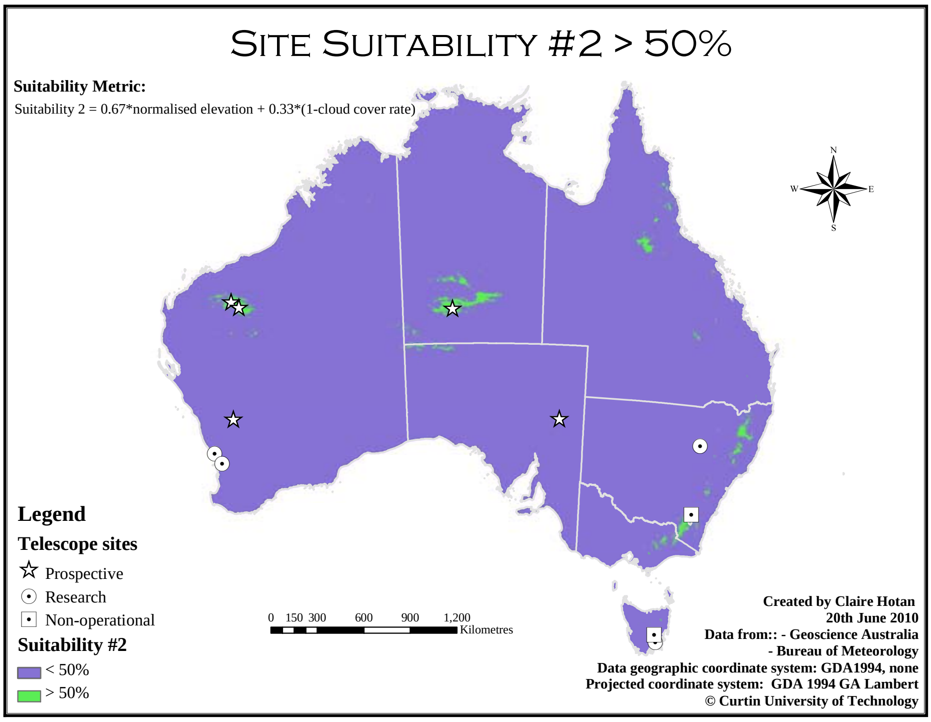

Figure 3.8: Map showing areas of Australia with metric #2 value > 0.5.

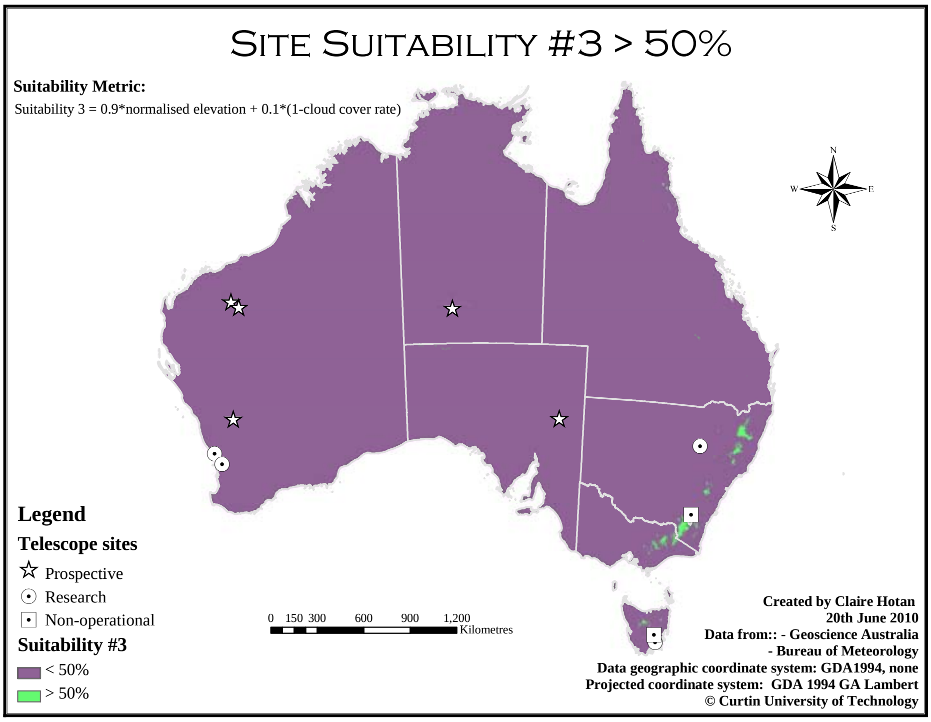

Figure 3.9: Map showing areas of Australia with metric #3 value > 0.5.

that for the first metric, where elevation and cloud cover are given equal importance, in other words, the case in which we value low cloud cover the most, Figure 3.7 shows that roughly anywhere in the Northwest third of Australia would be suitable, with the Southern and Eastern areas of the country excluded due to their relatively high rates of cloud cover. However when we consider the third case, in which 90% of the suitability comes from the site's elevation, we find that parts of the Great Dividing Range are considered suitable while large areas in the Northwest of the country are not. This is because there are some relatively high peaks in the great dividing range, so in some cases if the cloud cover in those areas is low enough, we will still rate them a suitable, even though they are likely to have a relatively low rate of photometric observing conditions, similar to and even worse than Siding Spring (N.S.W.). As one might expect, the results of the intermediate case metric produce suitability areas which are similar to both extreme cases. Less area is selected than in the first case but more than in the third, and much of that area is in the inland regions with moderate altitude and low cloud cover.

In this vein, we note that the Australian Astronomical Observatory, and indeed all the observatories located at the Siding Spring site in the Warrumbungle National Park, is in perhaps one of the best locations it could be within the constraints of being built an accessible distance from major cities, and likewise, the currently non-operational Mount Stromlo site appears to be a relatively good choice near Canberra. So while none of our existing research telescopes appear to be rated as "suitable" by any of the metrics used in this study, it is reassuring to know that at least the most major sites are at least about as good as they are going to be while balancing observing conditions with weather conditions and wishing to be located on, or at least near, the Eastern seaboard of Australia.

In the remainder of this section we discuss the identification of prospective telescope sites based on this analysis, and compare those sites to existing sites (such as Siding Spring, Mount Stromlo, Bickley, Gingin and Mount Canopus), and sites proposed previously by other authors (such as Mount Singleton (Walsh, 2004) and the Northern Flinders Ranges (Hogg, 1965; Coops et al., 1991; Wood et al., 1995)).

3.4.1 Identifying Potential Sites

As we discussed when presenting each of the three cases studied, each represents the metric for siting a different sort of telescope, or a telescope with a different set of scientific objectives. However it is apparent in the figures presented in Section 3.3 that some areas of Australia appear to perform consistently well over all metrics.

If we have a particular science objective, or potential telescope that we wish to site, we may concentrate on the most suitable metric, however in this instance where we are looking for typically excellent sites for prospective astronomical observing, then we consider the results produced in Figures 3.4, 3.5 and 3.6 to find locations or areas which promise to be capable of producing good results for any telescope which may be built. By inspection of these three figures in ArcGIS, we find that consistently across all three metrics, we see apparently suitable areas arising in the Hamersley Range in W.A. and the MacDonnell Ranges in the N.T., with both ranges having peaks of relatively high elevation (around 1200m in each). Case three, in which we placed the greatest importance on elevation, suggested better sites exist in the Great Dividing Range in N.S.W. and Victoria, however our results in Chapter 2 and from Case 1 (Figure 3.4) suggest that the cloud cover in these areas is sufficiently frequent that very good observing conditions would rarely be available. Furthermore from a meteorological perspective, prevailing winds around the globe, in particular across Australia, blow from West to East, meaning that we would expect better atmospheric stability over Western mountains than Eastern mountains. The particular details of cloud formation and medium–scale meteorology over the East coast of Australia is beyond the scope of this study, but may be considered a factor which could negatively impact on any sites selected in this region.

Thus based on this fairly basic method alone, of combining average cloud cover data with elevation data, we can propose sites which may in the future be tested for siting optical research telescopes in Australia. These sites are Mount Bruce (W.A.), Mount Meharry (W.A.), and the MacDonnell Ranges in the vicinity of Mereenie (N.T.). These sites have peaks of approximately 1200m (Mt. Bruce and Mt. Meharry) and 940m (MacDonnell Ranges), though it may be possible to find nearby locations with slightly greater elevations or slightly better atmospheric conditions.

3.4.2 Comparison of GIS-selected Sites with Previously Suggested Telescope Sites

These three sites which we have proposed as GIS–based candidates for hosting telescopes are now compared with other sites. To do this, we need to *extract* the actual suitability rating from each metric for each site of interest. This can be done using functions in ArcToolbox, a component of ArcGIS, producing a vector layer of the points of interest with values of the raster suitability layer(s). Table 3.1 shows the locations and suitabilities of the sites of interest in this study – present research sites, those proposed by other studies, and those proposed here. The table also shows the approximate elevation of each site, as well as a prediction of the approximate number of clear days for that site based on the regression (Equation 2.1) of Figure 2.8 using the pixel value at each site[7].

In Table 3.1 it is apparent that most of the currently existing research telescopes are not what we might consider to be ideally located, with suitabilities for each metric varying for each location. The Siding Spring Observatory fares remarkably well under the first metric of equal weighting of cloud cover and elevation with a suitability of 53%, considering that our primary reason for wanting to find a new telescope site is the frequent poor observing conditions at this site. However one should note that the sites in this table which have lower suitabilities in this metric are those we would expect to perform poorly under such weighting. These are the Perth Observatory in Bickley, and the Gingin Observatory, both in W.A., which are both in a latitude zone with dry summers but very wet winters (when the nights are longest and observing is ideally at its best), and both are at low elevations. Similarly outperformed in this metric are the defunct Mount Stromlo site (A.C.T.) and both Canopus Hill and the new Bisdee Tier site in

[7]Although the regression equation describing the line of best fit is unphysical in the limits of pixel values, in the range of pixel values representing continental cloud cover it can be taken to give an approximate value for the predicted number of days good observing at a site.

Tasmania. All "proposed" sites carry similar or higher suitability ratings under the first metric than Siding Spring. As the smaller research telescopes in Tasmania and Western Australia are used mostly for tracking, follow-up observations and large "search" collaborations (such as gamma-ray burst follow-up[8], supernovae detection[9] and the PLANET search[10]), this metric is the most suitable for describing their locations, and we note that unfortunately it would appear likely that none of these sites is what we might consider "well suited" to this observing, although all are probably at acceptable levels for this work.

As discussed in Section 3.3, the science performed by a telescope determines to some extent the metric that one should use to gauge the suitability of sites. We should then consider the functions played by each of the existing research telescopes. Since the demise of Mount Stromlo in January 2003 due to bushfire, the Siding Spring Observatory, hosting the Australian Astronomical Observatory and the Mount Stromlo Siding Spring Observatory, has been the primary, and virtually only, site of research observatories for optical astronomy in Australia. These telescopes are typically used for galaxy redshift surveys and similar science, and thus we wish to be in the regime around metric 2, that is, where elevation carries more weight than cloud cover, but cloud cover remains an important consideration. In this metric, Siding Spring is given a suitability value of 51%. It seems reasonable to hope that a very good site might have suitabilities around 50%, and indeed we see that three of the five proposed sites have equal or better suitabilities under the second metric than Siding Spring, with greater than 50% suitability ratings. Thus it appears reasonable to expect that if we wished to build a new telescope to perform similar work to that done by the telescopes

[8]Gamma-ray bursts may be studied in the optical regime through observations following circulars on the Gamma-ray bursts Coordinates Network (GCN) operated by NASA, http://gcn.gsfc.nasa.gov/.

[9]For example the Perth Automated Supernova Search (Williams, 1997).

[10]The PLANET collaboration searches for lensing and transit events which lead to discoveries of extra-solar planets (Sackett et al., 2004)

Latitude	**Longitude**	**Status**	**Name**	**State**	**Size**	**Elevation**	**Clear**[a]	***Suit1***	***Suit2***	***Suit3***
-31.2754	149.0672	Research	Siding Spring	NSW	3.9m	~1130m	114 days	53%	51%	48%
-42.8475	147.4330	Research	Canopus Hill	Tas	1.0m	~260m	40 days	20%	16%	11%
-32.0073	116.1367	Research	Perth Observatory	WA	0.6m	~390m	134 days	41%	34%	22%
-31.3560	115.7131	Research	Gingin	WA	1.0m	~50m	150 days	38%	25%	9%
-35.3190	149.0088	Defunct[b]	Mount Stromlo	ACT	1.9m	~770m	95 days	43%	40%	35%
-42.4259	147.2885	Pending[c]	Bisdee Tier	Tas	1.3m	~600m	40 days	27%	27%	25%
-29.4675	117.300	Proposed[d]	Mt. Singleton	WA	–	~670m	165 days	52%	42%	29%
-30.308	139.338	Proposed[e]	Freeling Heights	SA	–	~940m	177 days	48%	37%	21%
-22.608	118.144	Proposed[f]	Mt. Bruce	WA	–	~1200m	197 days	71%	65%	57%
-22.980	118.588	Proposed[g]	Mt. Meharry	WA	–	~1200m	201 days	72%	66%	58%
-23.886	132.200	Proposed[h]	Mereenie	NT	–	~950m	193 days	61%	53%	40%

Table 3.1: Locations, predicted clear days and suitability values for present and proposed telescope sites.

[a] Predicted number of clear days based on Equation 2.1 constructed by linear regression on known clear and cloudy day data from the Bureau of Meteorology shown in Table 2.1, where pixel values for each site are manually extracted using ArcGIS.

[b] Destroyed by bushfire in 2003 and not yet fully rebuilt.

[c] The University of Tasmania is relocating its primary observatory site from Canopus Hill to Bisdee Tier, this site is currently under construction.

[d] Proposed and studied by Biggs and Walsh (2004).

[e] Proposed by Coops et al. (1991) and also studied by Hogg (1965) and Wood et al. (1995).

[f] Proposed by Glazebrook (1999).

[g] Proposed in this study as an alternative to Mt. Bruce.

[h] Proposed in this study.

at Siding Spring, we would do well to consider siting it in the MacDonnell or Hamersley Range.

Finally, considering the suitabilities associated with the third metric, in which we place the greatest importance in elevation, as an indication of good seeing when conditions are photometric, we find that both Siding Spring and Mount Stromlo have relatively good values of around 48% and 35% respectively, while the other active research telescopes are much lower, between just 9% and 22%. We note that it would appear that the relocation of the University of Tasmania's primary observatory from Canopus Hill to Bisdee Tier should more than double the suitability of their site under this metric, in other words, in photometric conditions the observatory might expect to achieve significantly better seeing than had previously been possible, although resolution of less than 1 arcsecond remains unlikely (Cole, 2010). The two previously proposed and tested sites, Mount Singleton (W.A.) and Freeling Heights (S.A.) both appear to be good sites, but by this metric do not appear to hold any advantage over existing sites. In the case of Freeling Heights this appears to be in contradiction to the findings of Wood et al. (1995). Rather importantly on this topic, however, we notice that the proposed sites in Northwest Western Australia appear very well suited to this metric, with suitabilities over 50%, which as seen in Figure 3.9 is only possible in very few locations around Australia, most of which are otherwise excluded in the first two metrics for their poor cloud cover statistics.

Figures 3.10 – 3.17 give the reader a somewhat clearer understanding of each site considered in this study (with numerical results presented previously in Table 3.1). Each figure contains markers showing typical high and low values of suitability within that map, using the second metric presented (elevation is twice as important as cloud cover). As discussed in Section 3.3 the resolution of these maps is higher than that of the raw cloud cover data as we resampled this layer to match the DEM.

Figure 3.10 shows the existing telescope site at**Siding Spring**, New South Wales, hosting a number of research telescopes. This site is in a mountainous area surrounded by the Warrumbungle National Park. The site is a large distance from surrounding towns with no likely sources of light pollution within 10km of the site. The observatory is also at a high elevation, making this a good site for a telescope in the region. Frequent cloud cover however limits the suitability of the site somewhat.

Figure 3.11 shows the now defunct telescope site on **Mt Stromlo** near Canberra, once housing research telescopes prior to destruction of most of the site by a bushfire in 2003. This site is in the hills on the outskirts of the city, quite close to built-up areas. Consequently this site is likely to suffer ambient light pollution from Canberra, as well as experiencing frequent cloud cover.

Figure 3.12 shows the area containing the **Canopus Hill** observatory in Tasmania, a currently operational research observatory housing a 1.0m telescope, as well as the **Bisdee Tier** site where a new observatory is being built to house a 1.3m telescope. Due to frequent periods of cloud cover, this figure demonstrates that there are few "good" sites in Tasmania, however it is also clear from this figure that the new Bisdee Tier site represents a significant improvement over the previous site, being much further from built-up areas and potential sources of light pollution, as well as having a higher elevation. Note that the apparent areas of better suitability along the Eastern coastline are an artefact from the coastline superimposed on the cloud cover data image, and do not represent true suitability ratings.

Figure 3.13 shows the sites of the currently operational research telescopes near **Perth** and **Gingin** in Western Australia. The Perth Observatory in Bickley is close to the outer suburbs of Perth, and as such, is highly prone to ambient light pollution from the city and surrounds. However it is located at a much higher altitude than the Gingin observatory, which is located a good distance from likely sources of light pollution such that the sky-glow from Perth is a minor factor (although it is near a military area). Both sites produce good science results, but neither could be considered to be well located except for accessibility. Again note that the large areas of higher suitability along the coast are coastline artefacts from the cloud cover data, and not true suitability values.

Figure 3.14 shows the area around the **Freeling Heights** site in the Flinders Ranges (SA) near Arkaroola Village studied by Coops et al. (1991) and Wood et al. (1995) (near the Mount Searle site tested by Hogg (1965)). This area contains minimal human habitation, although there are many mines in the area. Mines may or may not have large safety lighting associated with them, so light pollution can only be judged accurately directly from the site(s) of interest. The remoteness of this site combined with its elevation makes it a good prospective site for telescopes, although we do not find in this study that it is in an area of particularly low cloud cover.

Figure 3.15 shows the area around the **Mt Singleton** site in Western Australia studied by Walsh (2004). The proposed site is at a higher elevation than the surrounding land for some distance, which could lead to unexpected atmospheric effects. The site is far from major areas of population, so is not expected to suffer significant light pollution, however there are a number of mines in the area which may affect the sky quality. This site has been proposed as a potential candidate for relocating the Perth Observatory, being very much further from the significant levels of light pollution experienced at the current site. Our study would suggest that while the site does not appear to be of particularly high suitability for a large telescope, it would likely be a good improvement if the observatory were to be relocated, similar to the site change in Tasmania.

Figure 3.16 shows the area in the **MacDonnell Ranges** in the Northern Territory suggested in this study for site testing for prospective telescopes. The area is mountainous and experiences particularly low levels of cloud cover. With much of the area being Aboriginal lands, there is limited development in the area, with few nearby farm stations or mines. It would be anticipated that the deep sky viewing from this site would be excellent, however the quality of seeing will be affected by the atmospheric effects in the area. Being far inland there is likely to be significant convection currents in the atmosphere as the air cools and warms during the day. Thus the true suitability of such a site would need to be determined by a long observational site testing campaign.

Finally, **Figure 3.17** shows the area in the Hamersley Range in the Pilbara region of Western Australia containing **Mt Bruce** and **Mt Meharry**. Both mountains have high elevations, though they are significantly different in shape. Mount Bruce has a station and large mine site located very nearby, which may produce significant levels of light pollution. Mount Meharry on the other hand is a significant distance from nearby homesteads and mines, and thus is likely to offer better deep-sky observing. Both mountains are in an area of particularly low cloud cover, being in the region below the tropical summer rains and above the temperate winter rains. From our study, this area contains a large extended region of high suitability sites which should be tested with an observational campaign to determine their true quality.

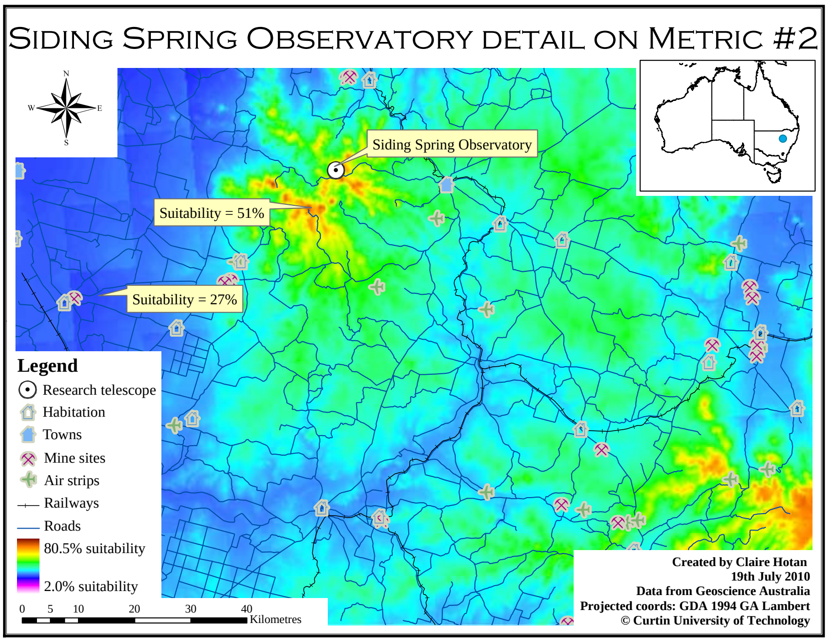

Figure 3.10: Map showing the area around the Siding Spring Observatory site.

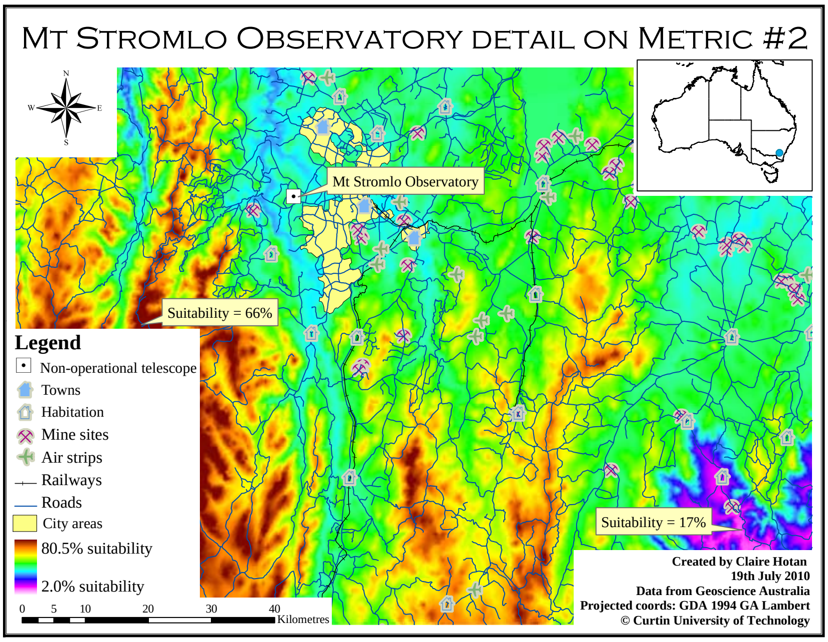

Figure 3.11: Map showing the area around the defunct Mt Stromlo site.

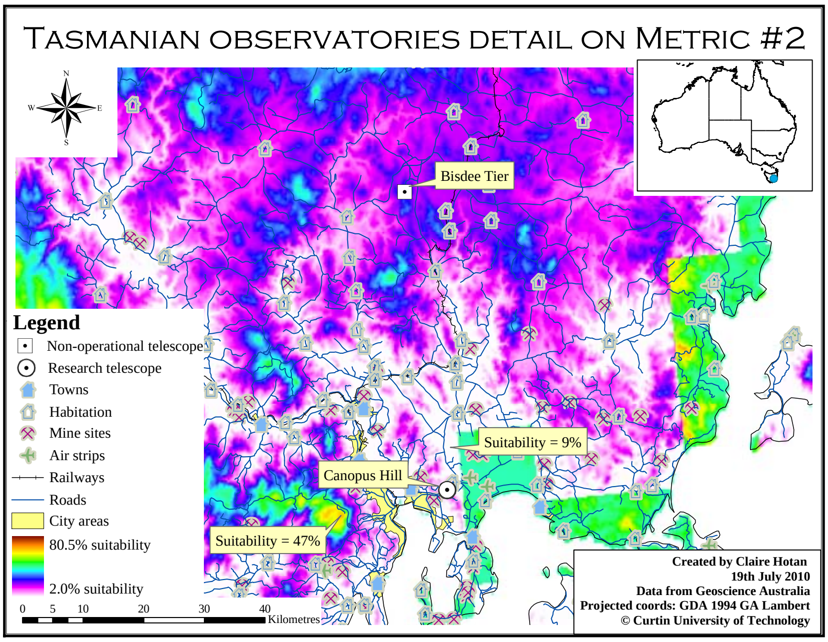

Figure 3.12: Map showing the areas around the old Canopus Hill observatory site and the new Bisdee Tier site.

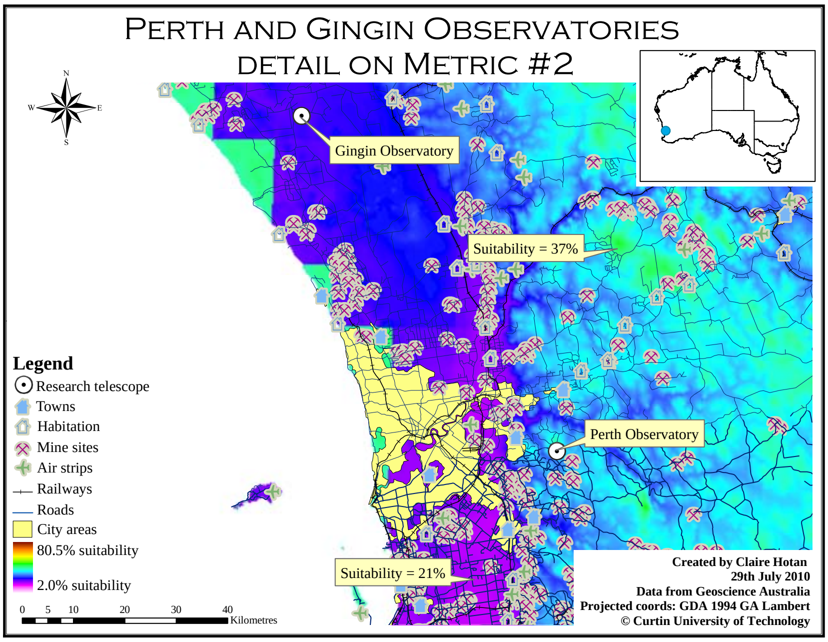

Figure 3.13: Map showing the areas around the current Perth Observatory and Gingin Observatory.

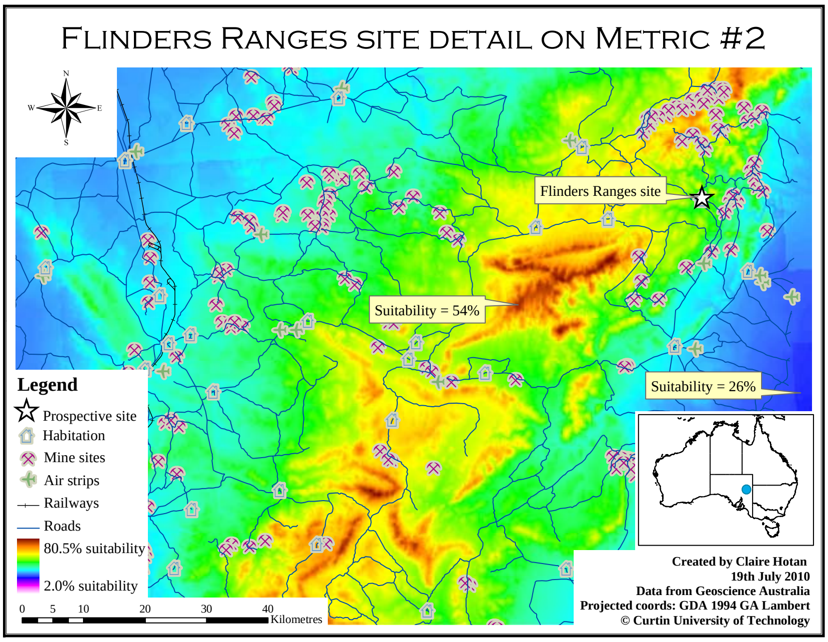

Figure 3.14: Map showing the area around the previously proposed Arkaroola site in the Flinders Ranges.

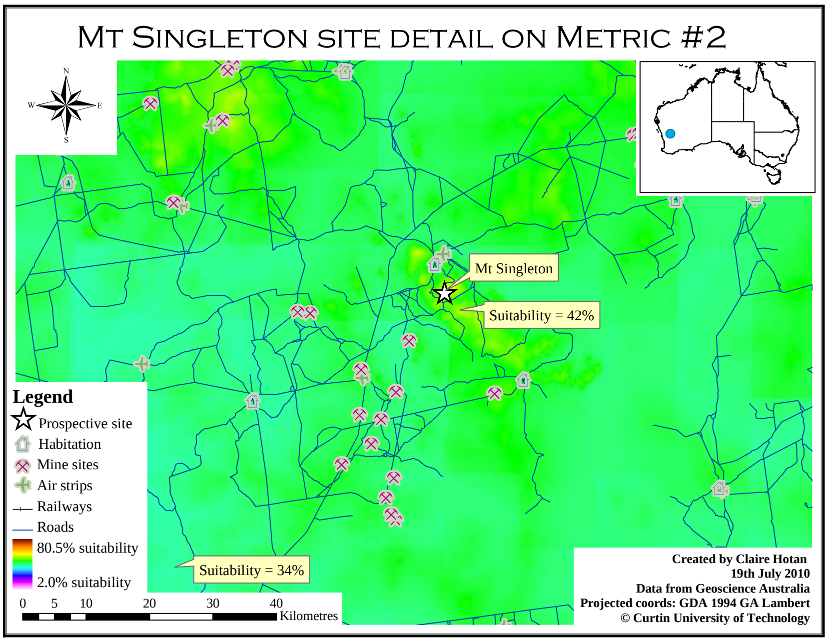

Figure 3.15: Map showing the area around the previously proposed Mt Singleton site in the Murchison.

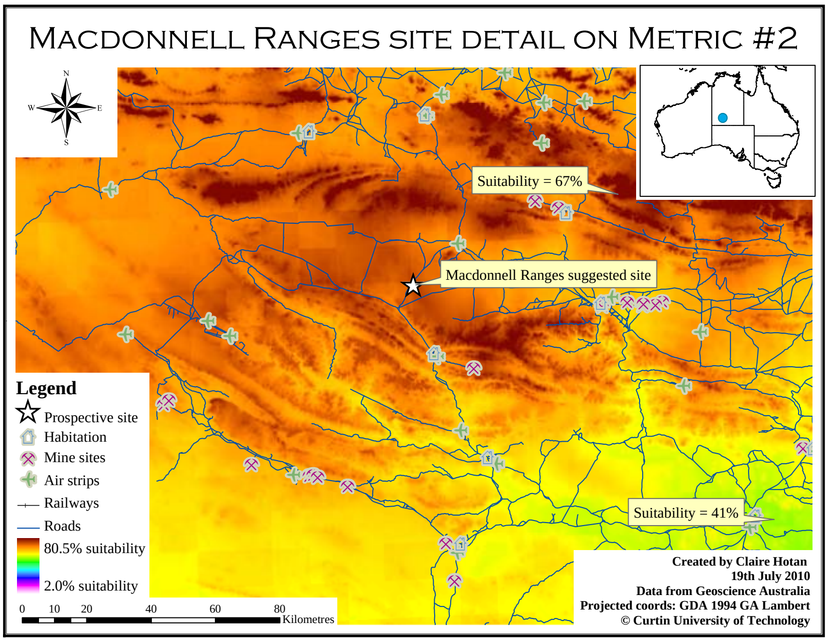

Figure 3.16: Map showing the area in the MacDonnell ranges which may be suitable for telescope site testing.

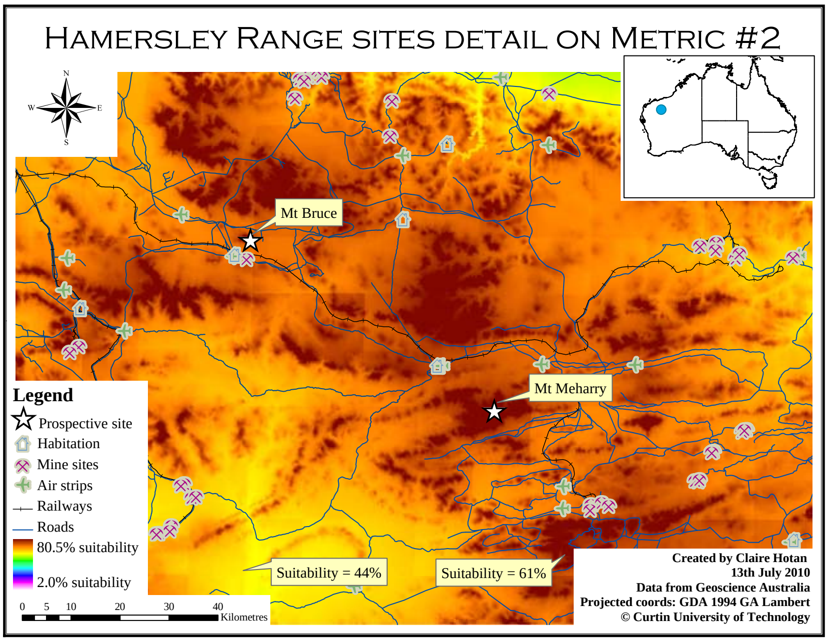

Figure 3.17: Map showing the area around the proposed sites in the Hamersley Range in the Pilbara.

3.4.3 Prospective Sites for a Large Optical Telescope in Australia

Hamersley Range, W.A.

The mountains in the Hamersley Range in the Pilbara region of Western Australia have been identified in a number of previous studies based on meteorological analysis of cloud cover patterns, from as early as 1974 by McInnes et al. (1974) who studied the whole globe, mentioning in passing the potential quality of observing in this region; through the more recent work of Coops et al. (1991), who focussed on a meteorological approach to telescope siting in Australia, concluding that the Flinders Ranges in S.A. and the Hamersley Range in W.A. both had good cloud statistics, but for accessibility reasons the South Australian site would be preferable. In the last few years astronomers have started to consider sites where accessibility concerns are not considered important, wishing instead to gain the best sites available, such as those on the Atacama Plateau of Chilé, and Dome C in Antarctica. Similarly in Australia we might make similar considerations, noting that even our most remote sites will be more accessible than those others, and that radio telescopes are already being built in very remote locations so as to make best use of the hardware by building it in some of the most ideal Radio Frequency Interference (RFI) free conditions available on the planet.

Under the assumption that we should be more interested in the goodness of a site than the practicalities of building on or accessing that site, Glazebrook (1999) performed a similar analysis to Coops et al. (1991) and McInnes et al. (1974) using infrared cloud cover and precipitable water vapour data to conclude that a mountain like Mount Bruce in the Pilbara region would be a potentially ideal, or rather, best site in Australia for a future optical telescope in this country.

Thus based on the information presented in Table 3.1 we might suggest that either of the two mountains identified in the Hamersley Range as good candidates should both be considered seriously and site testing performed at these sites.

At this point we should explain why there are two mountains selected in this area, rather than one. Based on the preliminary findings of Glazebrook (1999) it would seem reasonable to also propose Mount Bruce as an ideal candidate site, and this is in good agreement with our findings in both the meteorological only as well as GIS analysis. However, practical considerations do need to be taken into account, and in this case, the consideration in the third group of criteria suggested by Ardeberg (1983), of artificial light pollution. The population density of the proposed region is very low, so we would expect light pollution to be of little importance, however Western Australia is also very mineral–rich, and there are many mines throughout the outback regions. One such very large mine is located on the side of Mount Bruce, and so despite the height of the mountain, it appears likely that sky quality conditions may be adversely affected on this site. Thus while we wish to perform future site tests on this mountain, it is considered pertinent to also consider the nearby Mount Meharry, which is located within the Karijini National Park, and is therefore somewhat shielded from light pollution, as there are no mines immediately nearby the site. While Figure 1.3 shows that there is mine–related light pollution in the area, such images are difficult to georectify (due to sparsity and uneven spread of identifiable points) to sufficient accuracy to ascertain precisely where the light pollution in the North West area of Australia is with respect to these sites.

Another thing to note about these two mountains is that while they are geographically close together, they are rather different in shape, which may lead to differing air-flow patterns across their peaks, which could produce different seeing conditions at each site. Figures 3.18 and 3.19 show topographic data and are taken from Google Maps™, both at the same scale. Figure 3.18 shows Mount Bruce, which is a very tall, narrow mountain surrounded by otherwise flat land in the near vicinity. Access to the peak is limited and by foot only. Figure 3.19 maps the terrain around Mount Meharry, which is in the midst of a larger mountain range, and has a flatter ascent, so some vehicular access may be possible (as is suggested by 4WD guide books for the area). As discussed by McInnes et al. (1974), a favourable site should be coastal and have a stable column of laminar air-flow above it, as this will be related to improved seeing conditions, as discussed in Section 2.2.3. It might be expected that the air-flow pattern over Mount Bruce will be more favourable to our requirements, but from the perspectives of both artificial light pollution and atmospheric stability, both sites should be considered further.

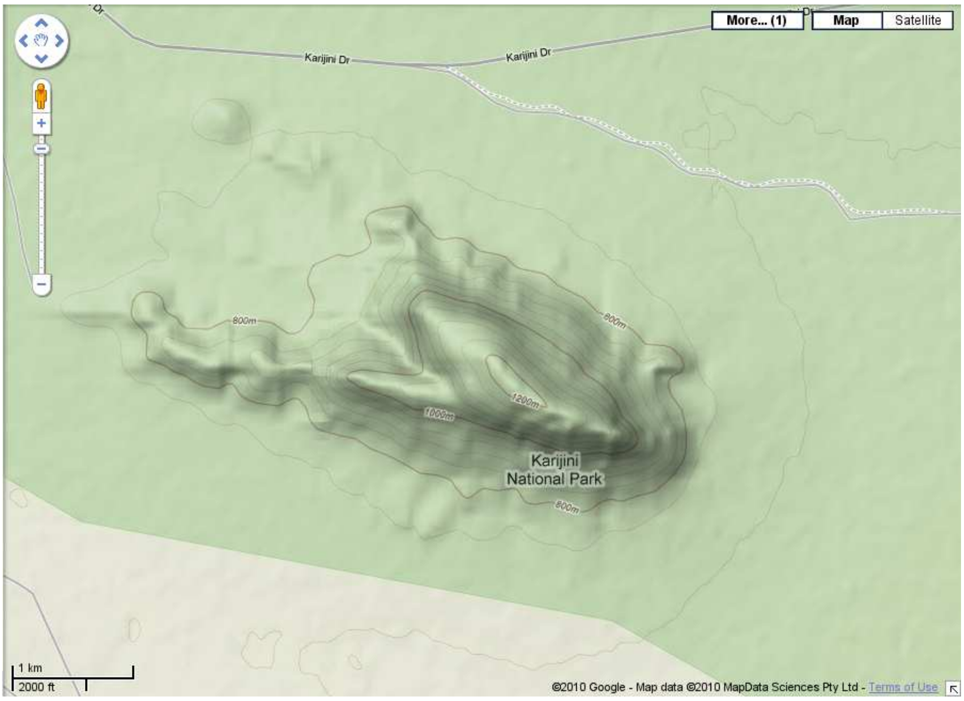

Figure 3.18: Terrain map of Mount Bruce, W.A. from Google Maps.

MacDonnell Ranges, N.T.

Based solely on our suitability calculations presented in Table 3.1, it appears that sites in the MacDonnell Ranges may be of similarly high suitability ratings to those in the Hamersley Range in Western Australia. Intuitively we would expect significant diurnal convection currents in this far inland region, and would not expect stable laminar air flows as might be experienced in western coastal areas. Nevertheless, based only on the suitability values computed, without access to

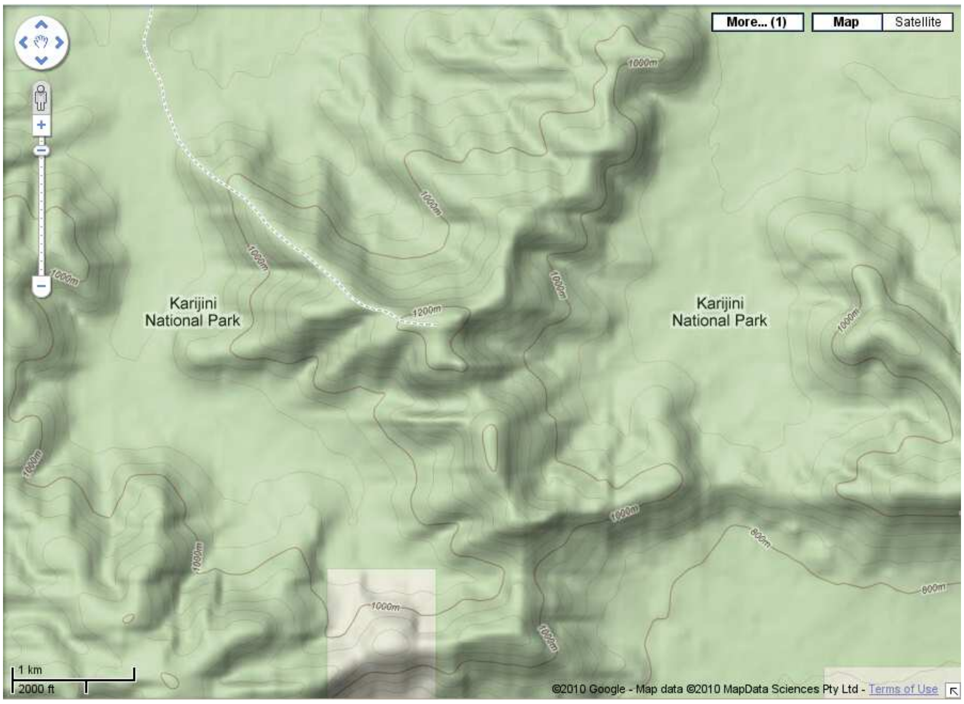

Figure 3.19: Terrain map of Mount Meharry, W.A. from Google Maps.

good atmospheric models for each area, we can not necessarily recommend the Hamersley Range sites over those potentially available in the MacDonnell Ranges, any distinction can be made only based on intuition. Ideally a far inland site such as that suggested near Mereenie, N.T., should also be physically tested to ascertain the atmospheric behaviour in this region.

3.5 Conclusions from Geographic Analysis

In this chapter we have described the principles of geographic analysis and in Section 3.1 discussed the importance of geographical analysis for telescope siting, and introduced GIS and MCDA. In Section 3.2 we described the process of using MCDA in this context, and presented the results of our analysis of three different metrics, or ways of combining our cloud cover and elevation data, in Section 3.3. Finally we compared the suitability values for each present and proposed telescope site in Section 3.4 and from this, we identify Mount Bruce and Mount

Meharry in the Pilbara region of Western Australia as being prime candidates for astronomical site testing, as this analysis suggests they are perhaps the most ideal locations in Australia for hosting optical telescopes.

Whilst it is beyond the scope of this project, an outline of how such site testing may proceed is described in Chapter 4.

Chapter 4

Testing of Potential Sites

It is widely considered that a vital part of any decision to site a major project must be accompanied by appropriate testing of the proposed site(s) to verify suitability. Historically, physical site testing was the only mechanism available for choosing astronomical observatory sites. However with the advent of satellite based meteorological data and the development of appropriate analytical software like GIS packages, more of the process can be handled remotely, which should save a significant amount of time by allowing early discrimination of better and worse sites.
Site testing for major telescopes has been carried out, including those studies by Hale (1905), Ardeberg (1983), Sarazin (1986), and Cowles (1991), and these tests are often ongoing (Bely, 1987; Sarazin, 1994; Puxley, 2001; Sarazin, 2010). Site testing is carried out at all prospective sites prior to the building and commissioning of telescopes. In Australia, for instance, Wood (1951) discussed telescope siting (prior to the construction of the Siding Spring Observatory), and testing of prospective telescope sites has been performed by Hogg (1965), Wood et al. (1995) and Walsh (2004).

Although time was not available during the execution of this research, in the future, field trips should be made to the best candidate sites to establish a remote testing station which could collect data on cloud cover and visibility, and thus confirm or reject the site as a suitable one for an optical telescope installation. Ideally this analysis would also be performed at an existing site to confirm measurement accuracy. The results of site testing should allow us to apply some quantitative figures to our qualitative suitability maps of Chapter 3.

It is worth considering the role of Adaptive Optics (AO) in modern astronomy (Beckers, 1993; Ellerbroek and Vogel, 2009). With real-time mirror deformation and the like in large telescopes, we are able to compensate to some extent for atmospheric turbulence. In the initial days of AO in the late 1990s this required a "guide star", but in recent years, techniques involving the use of a high–powered laser to create the guide star near the observing field have been mastered. Using these techniques, astronomers have been able to improve the resolution achievable with their telescopes. For example at La Palma (Canary Islands) improvements of up to 2× resolution can be achieved using Adaptive Optics compared to the uncorrected seeing, as discussed, for example, by Doel et al. (2000). Consequently if we have an ideal resolution, or Strehl ratio[1] that we wish to achieve, then we may be able to some extent, to substitute altitude for AO engineering. That is to say, we can potentially significantly improve the seeing of a telescope using AO, so that it performs as well as an uncorrected telescope at a higher altitude. Thus using adaptive optics in a telescope for which seeing is of primary importance, it may be possible for us to move away from the third metric (emphasising elevation) and instead place more importance on low cloud cover for the same potential telescope.

In this chapter we discuss possible methods for site testing in Section 4.1. In Section 4.2 we discuss our choice of sites at which tests should be performed. We go on to briefly mention comparisons with other relevant site testing studies in

[1]The Strehl ratio is a measure of how good the optics of a system are, and is calculated by comparing the peak intensity of the measured point spread function to that of an ideal diffraction limited point source, as described in Beckers (1993) and Ellerbroek and Vogel (2009).

Section 4.3, and finally in Section 4.4 we discuss the necessary future studies, which include extension of the GIS analysis presented in Chapter 3.

4.1 Methods Available for Site Testing

Site testing should be performed over as long a period as possible to eliminate seasonal and short-term climatic variations. Ideally we wish to be able to set up a remote observing station without the need for an astronomer or observer to be physically present at all times. This could be done using a fish-eye lens and webcam, connected to a secured and weather-proofed laptop or industry–grade field computer running an image processing algorithm which would detect the level of cloud cover, and if clear, ideally an estimate of the visibility. It is rather more easy to detect cloud cover during the daylight hours, but visibility and seeing measurements can of course only be made at night. As we would ideally perform our analysis using inexpensive commodity goods, accurate calibration of our measurements could require some fine tuning. For this reason we propose that this type of relatively low-cost site testing should be performed not only at the proposed "ideal" sites, but also at locations with known seeing values, such as at currently operational observatories. Furthermore we should compare our measurements across a range of apparent suitability areas, so that we would test remote locations as well as urban and regional areas in order to try to calibrate the qualitative GIS results of Chapter 3.

We are interested in measuring three things: *(1)* weather conditions, *(2)* "seeing" (resolution), and *(3)* "sensitivity" (brightness visibility). Ideally we should be systematic in our site testing, so if we are testing a range of sites, we should endeavour to standardise the elevation to a reasonable extent, so that we are varying (we hope) only the ambient light pollution levels (sensitivity). In the case of our "ideal" sites this may mean performing site testing (at least for a short period) near the mountain but at a lower elevation. We can then change our variables and hold site constant while varying elevation, which we would expect to have some impact on measured resolution (seeing) if we have a sufficiently wide range of elevations at the site (it may only be reasonable to expect measurable changes every 500m of elevation, or perhaps even more, but it might be valuable to know whether the seeing is indeed better at the top of a mountain than the bottom as we would expect). While this would help to calibrate our GIS maps, it is not relevant for the final location of a telescope, as for that we wish for the best regional conditions available, for which we would choose immediately the highest peak in the area. As such these tests should only be performed if sufficient time is available and the tests can be performed at low cost.

Our observing approach should cover the measurement areas listed above.

(1) **Weather conditions:** A weather station may be purchased which would measure temperature, humidity, air pressure and wind speed and direction, and may log these values at regular intervals. We could adapt a webcam or similar device to allow some (daylight) estimates of cloud cover (see Section 4.1.1 for further discussion). All this information needs to be transferred into a computer and logged at regular, say half-hourly, intervals. We would also need to know the altitude and phase of the Moon at any given time. A basic GPS unit should give a sufficient altitude estimate (especially in clear ground such as at our proposed sites), and lunar phase may be extracted from online astronomy almanacs or sky visualisation software. The phase of the Moon of course does not affect the quality of the site, but it affects the ambient brightness, so if our site testing is done over only a short period we need to know what phase the Moon is in; and in the case of cloud-detection software that we may write based on edge detection, for instance, we could incorrectly identify the Moon as cloud.

(2) **Seeing:** Astronomical seeing can be a fairly difficult thing to measure. Ideally we wish to use a small telescope (perhaps roughly 4–5″) to measure the seeing disc of one, or many, stars. This is a much more difficult prospect for a remote site than a local site, for a number of reasons. Nevertheless, we wish to gauge the effects of atmospheric thickness and turbulence at a site, and to do this, we measure the resolution achievable. We could take long exposure images of a star, and determine the angular resolution obtained as it appears to move in the image due to atmospheric propagation effects. We may also endeavour to monitor the intensity variation in the star(s) (that is, twinkling). These measurements would require some sort of telescope, not just a webcam, and a CCD imaging device attached to the telescope. A number of groups studying telescope sites have built seeing monitors (see discussion in Section 4.1.1), and it may be possible to take a lead from these other studies.

(3) **Sensitivity:** We wish for the sky at our observing site to be dark enough that we have a "deep" field of view, that is, we wish to be able to see high magnitude (low brightness) stars. This will be affected by natural light pollution, such as the Moon, and artificial light pollution, such as ambient spill-over from cities, towns and large mine–sites, and direct lighting interference locally at the site (street lights, building lights and so on). We may do this by buying a "Sky Quality Monitor" (discussed in Section 4.1.1), or using the telescope that we may already hypothetically have on site for seeing tests, we might for example image an open cluster of stars (Chaisson and McMillan, 2005) and compare our image to some "ideal" image, and estimate our sensitivity based on how many stars are visible and what the cut–off observable magnitude at the site is (over time, as any one reading may not be indicative).

4.1.1 Comparison with Previous Methods

The propositions above are purely hypothetical, and better, or cheaper, ways of site testing may well exist. In this section we discuss the site testing methods used by others in terms of measuring sky quality. It should be noted that for the very large telescope installations, site testing is expensive and well beyond the realms of what we are considering as reasonable for this project (see more discussion in Section 4.4).

There are commercially available sky quality monitors[2]. These allow us to estimate the ambient sky brightness at a site, and thus obtain a figure for measurement #3 above, the sensitivity. This method has been employed by the Perth Observatory[3].

To address measurement #2, the astronomical seeing at a site, the use of Differential Image Motion Monitors (DIMMs) has increased, since their inception by Sarazin and Roddier (1990) at the ESO through to the present day, where a DIMM is now considered fairly standard site measurement equipment. For example, the Perth Observatory have a DIMM which Walsh (2004) used in measuring seeing at the Bickley and Mount Singleton sites mentioned in Chapter 3.

In terms of measurement #1, the weather conditions, while the obvious solution is a weather station and a webcam or similar to detect cloud cover, this will only work during the daytime. Thus it has been the work of some groups to develop the same algorithms for use with infrared cameras (Hotan, 2001; Mallama et al., 2003; Shaw et al., 2005) in order to measure cloud cover day and night.

4.2 Sites Selected for Testing

In selecting trial sites for quantitative testing, we may wish not only to study the candidate telescope sites, but also to gather at least some short time-range data from other sites (maybe a week or two at an appropriate lunar phase and season), which we expect to have different ambient light conditions and different seeing conditions. As a guideline, artificial light pollution will be correlated with population centres (the predominant exceptions being mines and air fields).

[2]See for instance the Sky Quality Meter at http://www.unihedron.com/projects/darksky/.

[3]The Perth Observatory provide regular updates of their fish–eye camera at http://www.perthobservatory.wa.gov.au/information/po_sky_camera.html, and a 2009 3rd year project student from Curtin studied light pollution around the Perth metropolitan area.

The Australian Bureau of Statistics and Geoscience Australia both provide appropriate data for judging such factors, but ultimately we can probably choose sites based on local knowledge of urban, regional and remote areas. The sites suggested here are shown in Figure 4.1.

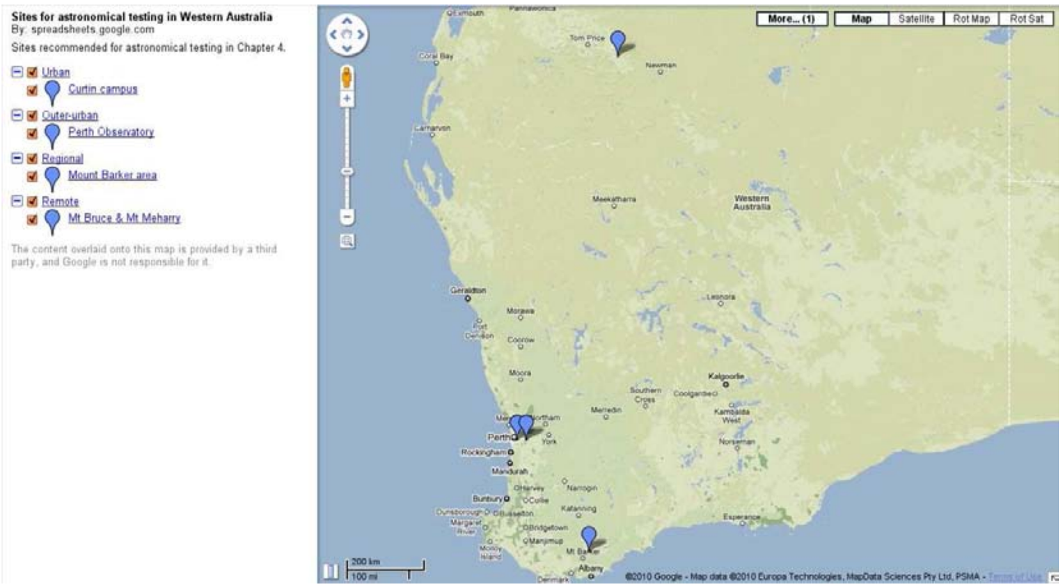

Figure 4.1: Google Map of Western Australia showing proposed astronomical testing sites.

4.2.1 Control Site: Urban

An urban test site should be located within the city's sky glow. For example an observing station on Curtin's main campus is sufficiently close to Perth to be a suitable site for this purpose. There is an astronomy observing deck near the Applied Physics building, however it is in a direct line–of–sight to the campus bus stop, which produces a lot of direct spill–over light pollution, and as such if we are interested more in ambient light pollution a different location on campus may be more appropriate.

As this site would be accessible at any time of year, even if testing is performed only occasionally it should be possible to get a fairly good measurement of our three variables of interest.

4.2.2 Control Site: Outer-urban – the Perth Observatory

An outer-urban test site would be located outside of the main city sky glow, but near enough that it interferes with observing in the direction of the city. For example an observing station located at Perth Observatory, Bickley, would be a good location, being a significant distance from the city centre, but still in a relatively densely populated area. Telescopes are already located at this site, being a professional observatory, and seeing and brightness measurements are regularly made by the staff and occasional students. This site has an elevation of a little under 400m above sea level, and we expect relatively high artificial light pollution due to its proximity to Perth city.

Sufficient temporal data points for this site should be attainable in conjunction with the regular monitoring done at the site as a matter of course, so long as the readings are taken with consistent instrumentation with that used at other sites.

4.2.3 Control Site: Semi-remote

A semi-remote test site would be located far from any significantly built-up areas like cities and major towns, but would be in areas with some population density, like regional farming districts. An example of such an area might be in the Southwest region of Western Australia. Anywhere in this region which is a significant distance from major towns should be appropriate, and we might suggest a location such as the hilly areas near Mount Barker, where there are a number of small towns in the region but is a good distance from significantly built-up population centres like Albany.

Testing such a site is probably not a high priority as it would not be a proposed telescope site, merely a control site to help quantify our suitability predictions. Furthermore, being so far from Perth, regular access to the site is not likely to be possible, so any site testing would likely have to be carried out only a few times over the course of a year, perhaps by taking the equipment to the chosen site and leaving it there for a week or two in various seasons. Thus data from such a site may well be sparse unless there is sufficient budget to build a full remote observing station for deployment at more than one site (because of course we would want our main station(s) to be the prospective telescope site(s)). Furthermore, the options for site testing such a site would be to camp at the site and monitor the equipment in person, or to leave it set up for some period and then return to collect the data. In that case, security of the site would also be very important.

4.2.4 Prospective Site

Our prospective site is a "remote site", far from major towns, in an area of low population density, at a high elevation and, we hope, sufficiently far from any mines, towns and airfields that there should be negligible ambient light pollution. The sites we are interested in testing are Mount Bruce and Mount Meharry in the Karijini National Park. While we expect that due to mining outside the national park but near Mount Bruce, light conditions may be better at Mount Meharry, we should test both sites due to their differing geography. Both have elevations over 1200m above sea level.

Testing of these sites may be quite a challenge. The tests need to cover a range of seasons, and ideally should be on-going over the period of observation, and the general meteorological trends compared against historical records hosted by the Bureau of Meteorology, for the closest available Bureau of Meteorology sites. If the site observing is done remotely, the test equipment on-site will need to be made secure, and an adequate power supply be available. The sites are so far from Perth that regular visits are likely to be very difficult, but these would provide the option to observe directly for periods of 1–2 weeks at regular intervals throughout the site testing campaign. The best approach to this problem would need to be solved by persons carrying out this site testing in the future, should it be decided that this would be practical and the likelihood of building or relocating a telescope is high.

4.3 Comparison with Previous Studies and Current Telescope Sites

While we have no results to report as physical site testing was deemed beyond the scope of a short project, we should mention the techniques used and results of other groups.

On-going monitoring of atmospheric conditions and weather is standard at all astronomical facilities, and in particular it should be straight-forward to compare any site results to logged data from the Perth Observatory (W.A.) or the Siding Spring Observatory (N.S.W.), though other sites may also have data which is available upon request.
The typical resolution available at Siding Spring is 1.2–1.3 arcseconds[4], though sub-arcsecond resolution is sometimes achievable, while the typical resolution at Bickley is typically around 1.2 arcseconds and greater (Walsh, 2004).

Both the site testing studies of Wood et al. (1995) and Walsh (2004) used the DIMM technology described by Sarazin and Roddier (1990).
In his study of Mount Singleton, W.A., Walsh (2004) used a DIMM provided by the Perth Observatory to take seeing measurements at three sites around the Bickley observatory, as well as at Mount Singleton in the Murchison region of Western Australia. This DIMM consisted of a 10–inch Meade LX50 telescope, SBIG ST–4 CCD camera and a laptop, as well as a custom DIMM mask (Walsh, 2004). Using this equipment, seeing values of 1.56 arcseconds, 0.88 arcseconds and 1.23 arcseconds for the ground, Lowell dome exterior and dome interior respectively were measured at the Perth Observatory; while at Mount Singleton more sub–arcsecond seeing was recorded, with a seeing peak value around 1.1 arcsec-

[4]AAT seeing typical resolution from
http://outreach.atnf.csiro.au/education/senior/astrophysics/atmosphere.html.

onds. These measurements were taken on 4 nights only for each site. These were in September 2003 and January 2004 (2 nights each) at ground level at Bickley; 4 nights in April 2004 (all 4 exterior to the dome, 2 interior after midnight) on the Lowell observatory dome platform; and 4 consecutive nights in January 2004 at Mount Singleton.
In their study of Freeling Heights in the Flinders Ranges, near Arkaroola, S.A., Wood et al. (1995) used a DIMM consisting of an 11–inch Celestron telescope, SBIG ST–4 CCD camera and a computer, with a two hole DIMM mask. Wood et al. (1995) took seeing measurements at both the Freeling Heights site and Siding Spring for comparison values. Using this equipment, which notably is a very similar set-up to that used by the Perth Observatory study, Wood et al. (1995) measured typical seeing values of 1.2 arcseconds at both sites, with best seeing values of 0.6 arcseconds at each site. However it was found that while the seeing values were comparable, Siding Spring recorded more poor seeing values (of more than 2 arcseconds) than did Freeling Heights. These measurements were taken in June–July and November–December of 1993, with 20 winter measurements and 12 summer measurements published for Freeling Heights, and 26 winter and 6 summer measurements published for Siding Spring.

For consistency, as these measurements were already made in Australia, it would be good to use the same or similar DIMM set up in furthering the work presented here in terms of implementing site tests. It is important to note that the work of Wood et al. (1995) is now 17 years old while that of Walsh (2004) is 6 years old, and climatic variations may have some impact on measurements in this time, however it is good to have figures to compare future measurements to.

For an idea of existing telescope locations for telescopes of all scales, see Appendix B, Figure B.2. These telescopes are typically near population centres, but usually in the nearest available dark sites, so this map is an approximate tracer of sky quality, though of course private astronomers simply base their telescope on whatever land they have available to them. Teaching sites are typically universities which are based in cities and so do not have good sky conditions but provide learning aids to school and university students.

4.4 Future Studies and Conclusions on Site Testing

In this chapter we discussed the need for physical site testing of prospective telescopes sites, covering the methods available for such tests on the level of this study in Section 4.1. In Section 4.2 we discussed a selection of 4 sites at varying distances from Perth that we propose should be performed to help us quantify our suitability values, or at least develop a better understanding of them. Section 4.3 explains the approach used by two other relatively recent telescope siting studies in Australia and their results.

It should be apparent that performing these site tests is an integral part of determining a site for any future telescope in Australia (or indeed, anywhere on Earth). Thus an initial extension to this research is naturally to perform the site tests suggested in this chapter and obtain seeing values at least for the proposed sites in Karijini National Park (Mount Bruce and Mount Meharry) and one in the MacDonnell Ranges. Based on rough seeing estimates[5] it appears likely that the proposed MacDonnell Ranges site(s) may typically achieve sub-arcsecond resolution, and although the elevation is typically similar to the W.A. mountains, they are far inland and thus likely to experience significantly different atmospheric conditions to any other site currently or previously studied in Australia.
While the methods proposed in this chapter would be those likely to be available

[5]For example the seeing estimates provided by "Meteoblue" for Alice Springs, N.T. can be found at http://www.meteoblue.com/en_US/point/forecast/tab/b/8/c/au/f/492.

to a graduate research student, ultimately before a large research telescope were sited, specific and expensive atmospheric studies would need to be performed using more professional equipment such as a MASS-DIMM (Kornilov et al., 2007), which is similar to the DIMM discussed above but with the capacity to judge atmospheric turbulence and boundary layers, and SODAR, a sound-based method of atmospheric profiling used to study the speed and stability of the air column above a site (Crescenti, 1997). Such equipment and testing would be a significant outlay, and it would not be preferable to test more than one or two sites with these methods, so the preliminary testing described above should be used to select the best, or few best, sites for future high-quality testing so that we can be confident in the predictions made by our GIS analysis.

As an intermediate step or in conjunction with site testing it may be possible to perform some atmospheric modelling algorithms to make predictions also. Atmospheric modelling has been used in the past with application to astronomy and predicting astronomical seeing by a number of authors including Coulman et al. (1986), Bougeault et al. (1995) and Masciadri et al. (1999). These models may include using "numerical meso-scale modelling" (Bougeault et al., 1995), the technique employed by the meteoblue website mentioned previously. Such models could be adapted and applied to the particular problem of seeing prediction within Australia or in specific regions.

In Chapter 5 we discuss the overall results of this study, and what future work is recommended in telescope siting to complete the work that this thesis may provide a base for, both in terms of the physical testing discussed in this chapter as well as the analyses discussed in the previous two chapters.

Chapter 5

Conclusion

5.1 Summary of Results

In this study we have investigated the prospective siting for any potential telescope to be built within Australia. In Chapter 2 we obtained infrared cloud cover data from the Bureau of Meteorology, which we combined to find trends in total cloud cover over the 18 month period June 2008 – January 2010. This analysis indicated areas of low cloud cover over the Northwest coast of Western Australia, extending inland to the Northern Territory. This is important, because a telescope should be operational for the maximum amount of time possible, and so should be located in a place where down-time due to inclement weather will be minimised.

In Chapter 3 we imported the total cloud cover image into GIS software, and combined it with a digital elevation model of Australia to find areas suitable for various types of telescopes, using three different metrics of weighting the importance of elevation (to minimise atmospheric disturbance and extinction) and cloud cover. While different weightings produced different results for appropriate sites, the mountains in Northwest Western Australia consistently performed well in all metrics, as they have both good elevations by Australian standards at around $1200m$, and very low cloud cover rates.

Due to their differing topography, however, despite their geographic adjacency, they may experience different atmospheric conditions in terms of stability and consistency of air-flow over their peaks. For this reason in Chapter 4 we recommend performing astronomical site tests at both Mount Bruce and Mount Meharry in this area, as well as a site in the MacDonnell Ranges in the Northern Territory, and propose methods for doing so.

5.2 Future Extensions to this Work

The initial and rather important extension to this work would be to perform the site tests discussed in Chapter 4 and obtain some empirical values for the astronomical seeing at the proposed sites at Mount Bruce and Mount Meharry in W.A., as well as ideally a site in the MacDonnell Ranges in the N.T., and comparison values from Perth Observatory, as well as Siding Spring Observatory. It may also be possible to collaborate to obtain equivalent values from the new Bisdee Tier Observatory in Tasmania.

Further work on this subject, in particular the geographic analysis component presented in Chapter 3, would also be necessary prior to making proposals to government or universities in terms of land acquisition and logistics. The land must be available for use or purchase. Geoscience Australia provides land use datasets and datasets which indicate areas of restricted access and aboriginal native title claims, which will be of high importance in the consideration of building a telescope.
Furthermore, studies need to be completed such as an Environmental Impact Assessment, to determine the presence or otherwise of endangered flora or fauna, and the impact that building and operating a telescope would have on these things. The outcome of such an assessment would also depend on whether the observatory is to be continuously manned, or if observing would be done remotely and the site accessed only for maintenance.

Another fairly straightforward extension is also to consider geological effects – we wish to know that the site is geologically stable, and, ideally, that we have access to bedrock to build on. In terms of potential future light pollution it will also be important to try to build in a protected area (such as deep within a national park), and that no significant mineral deposits which could become mining targets in the future lie within the "viewshed" of the proposed site. Again, mineral deposit data is available from GA, and ArcGIS provides the tools for computing the viewshed from a point based on the DEM, and from this viewshed we can extract any points in the layer of interest (mineral abundances, say), to discover what can and potentially *could* be seen from the site. A simple way to reduce the viewshed is to not build on top of a mountain, but we wish for any observatory to have as clear a view of as much of the sky as possible, and thus we would prefer to build on hilltops. If it is found that land is available at or near an appropriate site, then the very important advanced site testing described in Chapter 4 Section 4.4 to study the atmospheric stability over the favoured site should be performed. Applications may be made to preserve the lighting environment of the area ("Designated Observatory" status), which ideally should reduce the impact of future mining exploration and mine development in the area by legally requiring no light spill-over that would affect the observatory site.

We should ideally also extend the work shown in Chapter 2, to cover a longer time range, by obtaining the high resolution IR data from the BoM directly over as long a time-range as is available for that satellite. This would require some expenditure for the purchase of the data (at potentially significant cost), but would allow more accurate averaging to produce the mean cloud cover imagery shown. It would also be preferable to obtain Precipitable Water Vapour data, for example from the MODIS satellite, and perform an equivalent analysis to the cloud cover to determine water vapour content of the atmosphere, which may not always trace cloud cover and will affect seeing for a site, and is likely to be particularly important in coastal areas. Ideally a number of climate models should also be studied to look not only at present and recent past meteorological suitability of a site, but to also make a range of predictions as to how the stability of the airmass over the site may change in the future and whether we would predict the goodness of the site will improve or worsen over the medium term of its operation.

The extension to a longer time period of data and also more data layers such as precipitable water vapour could also be achieved through use of the FriOWL software (Sarazin et al., 2006), and while the resolution of these data are lower than is used in our analyses, the extended time period and extra layers available may be valuable in furthering this work, particularly the inclusion of precipitable water vapour, and air currents.

5.3 Final Remarks

At this time there are no plans to build any new large optical telescopes for research in Australia. Current efforts are going towards construction of very large telescopes consisting of arrays of mirrors on sites like the Atacama Plateau in Chilé and Mauna Kea in Hawai'i. Chilé has significant desert areas at altitudes over 2000m which rarely experience cloud cover and virtually never any rainfall, with some areas (such as the Atacama Plateau) reaching elevations of 5000m which suffer little atmospheric extinction in the infrared wavebands. Mauna Kea has an elevation of around 4200m, putting its peak above most levels of cloud, so that it suffers little atmospheric extinction. Both areas have laminar air-flows over their high peaks, and experience very minimal levels of rainfall. Both these areas, as well as La Palma in the Canary Islands and Dome C in Antarctica, are highly favourable sites for building significant optical and infrared astronomy installations on Earth.

Australia has little to offer in terms of being able to host the types of telescopes that are being built or are proposed for these areas. However there is a strong case for follow-up work, to add another large optical telescope in the Southern Hemisphere which is relatively close to future world-class radio astronomy installations (potentially including the Square Kilometre Array). Large amounts of observing time are also likely to be available on a significant, but smaller telescope, such as is currently done with the Australian Astronomical Telescope at Siding Spring. As the next generation of large telescopes come online in the higher, drier places on Earth (and even in space), it will be important to build intermediate research grade telescopes to complement the largest telescopes by providing opportunities for follow-up studies and to complement wide-field surveys. These new telescopes will need to be progressively larger to adequately provide the sensitivity required for this work.

To this end, a study into siting for future telescopes which could be built in Australia as the next generation of large optical telescopes comes online is a question worth considering, and we believe that the mountains in the Hamersley Range in Western Australia are likely contain the most appropriate sites in Australia to do this.

Appendix A

Code Written for this Project

A.1 BoM File Retriever

In Section 2.3.2 - Data periods, a description of the code `BoM_file_retriever.py` to retrieve files from the Bureau of Meteorology's low resolution GMS imagery file server was given. The code used to get these files was written using the Python language, and is given below.

```
# Retrieve IR satellite images from the Bureau of Meteorology
(www.bom.gov.au)

# USAGE: python BoM_file_retriever.py START_YEAR
# Start year must be from 2004 onward for this to work properly.

# Uses wget to retrieve all files for each day, month by month
from January in the year specified to the end of the present
year (i.e. now).
# Filenames are of the form IDE[sat_code].yyyymmddhhmmss.jpg
where time is in UTC.

# At this time it is not possible to specify the start date/time
```

```
or channel number, but that's probably okay. NOTE, however, that
we do not want to use any files before June 2004.

# The computer checks to see if it already has each file, and
if so, skips it. Otherwise, attempts to retrieve it. If this
fails, it is noted in a log and the null file removed. This log
should later be checked in case the failures are due to a server
issue and not non-existence.

import subprocess
import time
import os
import sys

startyear = int(sys.argv[1])
#Input year to start retrieving data from.

yearnow=time.localtime()[0]
#This means this file can be re-run at any time and we don't
need to fix the end of the years loop.

months = ["January", "February", "March", "April", "May", "June",
"July", "August", "September", "October", "November", "December"]

workdir = "/home/cehotan/Documents/Masters/GMSimages/BoM_wget"

success_file = open('/home/cehotan/Documents/Masters/GMSimages/
got_files.txt', 'a')
success_file.write("All times are in UTC.\n")
```

```
success_file.flush()
fail_file = open('/home/cehotan/Documents/Masters/GMSimages/
failed_files.txt', 'a')
fail_file.write("All times are in UTC.\n")
fail_file.flush()

os.chdir(workdir)
# Make sure we're starting in the images directory for year in
range (startyear, yearnow+1):
    yy = str(year)
    if os.path.exists(workdir+"/"+yy) == False:
         subprocess.Popen([r"mkdir",yy]).wait()
# Equivalent to os.mkdir(yy)
    os.chdir(yy)
#Shoud be the same as subprocess.Popen([r"cd",yy]).wait()
    for month in range (1, 13):
        if month < 10:
            mo = '0'+str(month)
        else: mo = str(month)
        if os.path.exists(workdir+"/"+yy+"/"+mo) == False:
            subprocess.Popen([r"mkdir",mo]).wait()
        os.chdir(mo) #subprocess.Popen([r"cd",mo]).wait()
        for date in range (1, 32):
            if date < 10:
                dd = '0'+str(date)
            else: dd = str(date)
            print "Getting files from", dd, months[month-1], yy
            for hour in range (0, 24):
                if hour < 10:
```

```
                    hh = '0'+str(hour)
                else: hh = str(hour)
                for mins in range (0,2):
                    if mins == 0:
                        min = '00'
                    elif mins==1:
                        min = '30'
                    filename=workdir+"/"+yy+"/"+mo+"/IDE00009.
"+yy+mo+dd+hh+min+"00.jpg"
                    if os.path.exists(filename)==False:
#Check if the file already exists, only do anything if not.
                        status=subprocess.Popen([r"wget","-q",
"-t","0","-O",filename,"http://www.bom.gov.au/sat/archive_new/
gms/ir1/"+yy+"/"+mo+"/IDE00009."+yy+mo+dd+hh+min+"00.jpg"]).wait()
                        if status == 0:
                            gotit = "Retrieved file "+yy+" "+
months[month-1]+" "+dd+" "+hh+":"+min
                            success_file.write(gotit+"\n")
#print to a record of "got files"
                            success_file.flush()
                            print gotit
                            time.sleep(5)
                        elif status != 0:
# If the file doesn't exist, record that.
                            dontgotit = 'Failed to retrieve file
'+dd+" "+months[month-1]+" "+yy+" "+hh+":"+min
                            print dontgotit
                            fail_file.write(dontgotit+"\n")
#print to a record of "not files"
```

```
                            fail_file.flush()
                            subprocess.Popen([r"rm",filename]).
wait()
#If the file doesn't exist we don't want to create a null file
with its name, we just want it not to be there at all, so delete
the placeholder file.
                            time.sleep(2)
                    else: print "File at "+dd+" "+months[month-1]
+" "+yy+" "+hh+":"+min+" exists, skipping this file."
#If it does exist we don't need to replace it, so just move on
to the next file.
        os.chdir(workdir+"/"+yy)
    os.chdir(workdir)
success_file.close()
fail_file.close()

# in wget:
# -t = number of tries put t=0
# -O = output document SPECIFY

# End of script.
```

A.2 Filter to Select Data Images

In Section 2.3.3 – Low-resolution data, we describe the code filter_ims_Aus_not_0.py which determines which low-resolution disc images contain data in Australia, discarding those which do not, and cropping to a boundary enclosing only Australia those which do contain data. These cropped files are then saved to a new directory for further analysis. This script was written in the Python language, and is shown below.

```
 # Load each image and check that Australia is present
(satellite data includes cloud cover for Australia), regardless
of the status of the Northern hemisphere.
# Then crop to Australia only

#USAGE: python filter_ims_Aus_not_0.py START_YEAR END_YEAR
#Where start year is the year to start checking data from.
Must be at least 2004. (at this time).

#PROCESS: Get files. Run this filter. Manually copy out remaining
"hourly" files as we want a fairly equal number of files at any
time of year in any year, so given it's mostly hourly that will
be missing, we'll move out all of them (into GMS_images/Hourly).
Delete May 2004. By eye, scan through each folder and move any
remaining dud files (such as where problems have occurred in the
satellite scan) to GMS_images/Quarantine. That means some files
will be cropped and moved to the next stage even though they may
still be corrupted. We just have to try to check manually.

import subprocess
from PIL import Image
import os
```

```
import time
import sys

print "Usage: python filter_ims_Aus_not_0.py YYSTART YYEND"
startyear = int(sys.argv[1]) #Year to start getting data from.
endyear = int(sys.argv[2])

workdir = "/home/cehotan/Documents/Masters/GMSimages/BoM_wget"

quarantine = open('/home/cehotan/Documents/Masters/GMSimages/
quarantined.txt', 'a')
quarantine.write("The following files appear to contain no data
in Australia and have been moved to GMSimages/Quarantine\n")
quarantine.flush()

#funky for loop to get them all
for year in range (startyear, endyear+1):
    yy = str(year)
    if os.path.exists(workdir+"/"+yy) == False:
        subprocess.Popen([r"mkdir",yy]).wait()
# Equivalent to os.mkdir(yy)
    os.chdir(workdir)
    os.chdir("..")
    os.chdir("Cropped")
    if os.path.exists("/home/cehotan/Documents/Masters/GMSimages
/Cropped/"+yy) == False:
        subprocess.Popen([r"mkdir",yy]).wait()
    os.chdir(yy)
    for month in range (1, 13):
```

```
        if month < 10:
            mo = '0'+str(month)
        else: mo = str(month)
        if os.path.exists(workdir+"/"+yy+"/"+mo) == False:
            subprocess.Popen([r"mkdir",mo]).wait()
        if os.path.exists("/home/cehotan/Documents/Masters/
GMSimages/Cropped/"+yy+"/"+mo) == False:
            subprocess.Popen([r"mkdir",mo]).wait()
        os.chdir(mo)
        for date in range (1, 32):
            if date < 10:
                dd = '0'+str(date)
            else: dd = str(date)
            for hour in range (0, 24):
                if hour < 10:
                    hh = '0'+str(hour)
                else: hh = str(hour)
                mm='30'
                if os.path.exists(workdir+"/"+yy+"/"+mo+"/
IDE00009."+yy+mo+dd+hh+mm+"00.jpg") == True:
                    im = Image.open(workdir+"/"+yy+"/"+mo+"/
IDE00009."+yy+mo+dd+hh+mm+"00.jpg")
#Pixels have values in (r, g, b), but as we are working in
monochrome all values are equal, so we just need the first one.
                    val1=im.getpixel((116,296))[0]
# Around Tom Price, W.A.
                    val2=im.getpixel((161,269))[0]
# Near Katherine, N.T.
                    val3=im.getpixel((208,333))[0]
```

```
# Near Albury-Wodonga, N.S.W./Vic.
                    val4=im.getpixel((203,297))[0]
# Near Longreach, Qld.
                    val5=im.getpixel((172,313))[0]
# Near Coober Pedy, S.A.
                    val6=im.getpixel((126,329))[0]
# Near Katanning, W.A.
                    val7=im.getpixel((227,314))[0]
# Near Lismore, N.S.W.
                    val8=im.getpixel((206,352))[0]
# Middle of Tasmania

                    tot_val=val1+val2+val3+val4+val5+val6+val7+val8

                    if tot_val < 160:
#This means that all cells can be up to 20 and it will still
be discarded - if there is data it's highly unlikely they'll
all be so low.
                        nodata = "Image "+yy+mo+dd+hh+mm+"00 does
not contain data and will be quarantined.\n"
                        print nodata
                        subprocess.Popen([r"mv",workdir+"/"+yy+
"/"+mo+"/IDE00009."+yy+mo+dd+hh+mm+"00.jpg","/home/cehotan/
Documents/Masters/GMSimages/Quarantine/"]).wait()
                        quarantine.write(nodata)
                        quarantine.flush()
                    else:
                        cropim=im.crop((95, 250, 240, 360))
                        cropim.save("/home/cehotan/Documents/
```

```
Masters/GMSimages/Cropped/"+yy+"/"+mo+"/IDE00009."+yy+mo+dd+hh+
mm+"00_crop.jpg")
        os.chdir("..")
#Use a full year/month/day directory structure here too so I can
combine by month, season etc. Put the cropped images back where
they came from, then once all are done, reproduce the directory
structure (with ALL files) in the "cropped" directory, and remove
all not-cropped images.

quarantine.close()

#End of script
```

A.3 Script to Sum Images

In Section 2.3.3 – Low-resolution data, we briefly describe the algorithm code which combines our cropped images to give a total summed image that is the average of all cropped images. This is done in two ways, initially using "blank" images, which is an image the same size as the cropped images but contains only 0s (it is black); the second method weights the combination of files to make sure all have equal weighting in the final image, but uses no blank images that could affect the final pixel values.

The script was run on the Curtin Institute of Radio Astronomy's "CUPPA" cluster, as the large number of files combined in this analysis required significant amounts of RAM not available on a desktop computer.

The same script is used for the high-resolution data – for the whole dataset, day images, night images, summer, winter and shoulder seasons, with the work directory, script name and output files modified accordingly. In the final iteration for the high-resolution data the "blanks" section was removed, so only the second algorithm was used.

The scripts that work in this manner used in this thesis are:

`sum_IDE00009_cuppa.py`

`sum_mono_ims_CUPPA_Jan10_noblanks.py`

`sum_mono_day_ims_CUPPA_Jan10_noblanks.py`

`sum_mono_night_ims_CUPPA_Jan10_noblanks.py`

`sum_mono_summer_ims_CUPPA_Jan10_noblanks.py`

`sum_mono_winter_ims_CUPPA_Jan10_noblanks.py`

`sum_mono_shoulder_ims_CUPPA_Jan10_noblanks.py`

```
# Using the cropped IR images, sum all images.
#USAGE: python sum_IDE00009_cuppa.py
#Requires cropped images to be in /arch/cehotan/Cropped


from PIL import Image
```

```
import os
import math

workdir = "/arch/cehotan/Cropped"

#Count how many files we need
(this is the total we need to scale by)

npics = len(os.listdir(workdir))
print "Found "+str(npics)+" files to add."

#Sort images into time order
by_time = sorted(os.listdir(workdir))

#Figure out how many powers of 2 I need to cover all available
images (hence how many blanks are needed)
n=1
i=1
while i:
    p=2**n/npics
    if math.floor(p)==1:
        i=0
    elif math.floor(p)==0:
        i=1
        n=n+1
num_black=2**n-npics
print "Need "+str(n)+" layers, ie. "+str(2**n)+" images.
Therefore add "+str(num_black)+" black images."
```

```
#Set up list of lists to store images in
imlists={}
imlists[1]=by_time
for s in range (0, npics):
    imlists[1][s]=workdir+"/"+by_time[s]
for r in range (2, n+2):
    imlists[r]=2**(n-r+1)*[0]
#add blank images to first column
for t in range (1, 2**n-npics+1):
    imlists[1].append(workdir+'/Blackim.jpg')

#Iteratively merge pairs of images, using blanks to make up to
a power of 2 (ie a tennis tournament but with 'null matches'
instead of wildcard entires).
#Save each blended image in the next row of the lists list.
for l in range (1, n+1):
    for j in range (0, 2**(n-l)):
        print "l="+str(l)+" j="+str(j)
        if l==1:
            imone = Image.open(imlists[l][2*j])
            imtwo = Image.open(imlists[l][2*j+1])
            print "Opening files "+imlists[l][2*j]+" and "+
imlists[l][2*j+1]+"."
        else:
            imone = imlists[l][2*j]
            imtwo = imlists[l][2*j+1]
            imone = imone.convert("RGB")
            imtwo = imtwo.convert("RGB")
            print "Opening "+str(imlists[l][2*j])+" and "+str
```

```
(imlists[l][2*j+1])+"."
            print str(imone.size)+" "+imone.mode+" "+str(imtwo.
size)+" "+imtwo.mode
        imlists[l+1][j]=Image.blend(imone,imtwo,0.5)
        imlists[l][2*j]=0
        imlists[l][2*j+1]=0
finalim=imlists[n+1][0]
finalim.save("/arch/cehotan/blend_IDE00009.jpg")


#Sum without using blanks
#Only this section used for the final high-res images
imlists2={}
spare=[]
by_time = sorted(os.listdir(workdir))
imlists2[1]=by_time
for s in range (0, npics):
    imlists2[1][s]=workdir+"/"+by_time[s]
for r in range (2, n+2):
    imlists2[r]=[]
for a in range (1, n+1):
    for b in range (0, int(math.floor(len(imlists2[a])/2))):
        print "a= "+str(a)+" b="+str(b)
        if a==1:
            imone2 = Image.open(imlists2[a][2*b])
            imtwo2 = Image.open(imlists2[a][2*b+1])
            print "Opening files "+imlists2[a][2*b]+" and "+
imlists2[a][2*b+1]+"."
        else:
```

```
            imone2 = imlists2[a][2*b]
            imtwo2 = imlists2[a][2*b+1]
            imone2 = imone2.convert("RGB")
            imtwo2 = imtwo2.convert("RGB")
            print "Opening "+str(imlists2[a][2*b])+" and "+str
(imlists2[a][2*b+1])+"."
            print str(imone2.size)+" "+imone2.mode+" "+str(imtwo2
.size)+" "+imtwo2.mode
        imlists2[a+1].append(Image.blend(imone2,imtwo2,0.5))
        imlists2[a][2*b] = 0
        imlists2[a][2*b+1] = 0

#Spare bit
    spare.append(int((float(len(imlists2[a]))/2-len(imlists2[a])
/2)*2))
    print str(spare)
    if spare[a-1]==1:
        ones=spare.count(1)
        print ones
        if ones%2==0:
# Here % = mod (|) ie 6|3=0, 6|4=2.
            spare.reverse()
            a2=spare.index(1,1)
            spare.reverse()
            a2=float(len(spare)-a2)#-1
            q=float((2**a2)/(2**float(a)+2**a2))
            a2=int(a2)
            print a, a2, q
            print "Weight of combining set = "+str(q)
```

```
            bnew=len(imlists2[a+1])#+1
            imonex2 = imlists2[a][len(imlists2[a])-1]
            imonex2 = imonex2.convert("RGB")
            if a2==1:
                imtwox2 = Image.open(imlists2[a2][len(imlists2
[a2])-1])
            else:
                imtwox2 = imlists2[a2][len(imlists2[a2])-1]
            imtwox2 = imtwox2.convert("RGB")
            imlists2[a+1].append(Image.blend(imonex2,imtwox2,q))
print "Length of imlists2 is "+str(len(imlists2))
print "n= "+str(n)
print "imlists2 last is "+str(imlists2[len(imlists2)-1])+" or "
+str(imlists2[len(imlists2)])
finalim2=imlists2[n+1][0]
finalim2.save("/arch/cehotan/blend_IDE00009_noblanks.jpg")

#End of script
```

A.4 Script to Sum Images Without Loss of Dynamic Range

In Section 2.3.3 we discuss the need to show that the results produced by the code in A.3 are not limited by being restricted to 8-bit values (pixels in the range 0 to 255) during calculations, which effectively forces each added image to a range of 0 to 127 prior to adding. To demonstrate this we wrote another code, `sum_mono_ims_CUPPA_Aug10_floats.py`, to add the images directly:

$$Totalcloudcover = \frac{\sum_{i=1}^{n} image_i}{n}. \tag{A.1}$$

We do this using the PIL module ImageMath, which permits mathematical operators such as addition and scalar division on images, as shown in the following code. ImageMath automatically adjusts the number of bits used to store data to avoid overflow problems, so 8-bit limitations are avoided as it moved readily to floats or large integers, which we force here by converting our first image to floats (by default, 64-bit).

```
#Using the IR images, sum all images and correct (/number).
#Do this by loading each image but converting to a float array,
sum all, average and output back to image file.
#Convert and sum using ImageMath.

from PIL import Image, ImageMath
from numpy import *
import os
import math
import matplotlib.pyplot

workdir = "/arch/cehotan/BoM_ftp/IDE05"
```

```
#count how many files we need (this is the total we'll need to
scale by)
npics = len(os.listdir(workdir))
print "Found "+str(npics)+" files to add."

#sort images into time order
by_time = sorted(os.listdir(workdir))

#Load each image in; convert to float array and add it to the
running total array.
imagefiles = []
for s in range (0, npics):
    imagefiles.append(workdir+"/"+by_time[s])
#Load and sum images
imagetotal = Image.open(imagefiles[0])
imagetotal = imagetotal.convert("F") #First image as float
for t in range (1, npics):
    print "Opening file "+imagefiles[t]
    imaget = Image.open(imagefiles[t])
    imaget = imaget.convert("L") #Convert to luminosity
    imagetotal = ImageMath.eval("a+b",a=imagetotal,b=imaget)
#Normalise back by dividing by npics
imagetotal = ImageMath.eval("a/t",a=imagetotal,t=npics)
print "Making final image..."
imagetotal.save("/arch/cehotan/BoM_ftp/sumallmono_imagemath_
010910.gif","GIF")
print "Done! :)"
# End of script.
```

A.5 Seasonal and Diurnal Image Sorting Scripts

The code given in Appendix A.3 covers a variety of datasets. For the high–resolution data, we summed the entire dataset, but also looked at seasons and days and nights, as we expect different behaviours across the continent in Summer and Winter (`seasonal_im_sorter.py`). The Summer data was extracted by using all data from December, January and February; the Winter data by using all data from June, July and August; and the shoulder season data from April and October.

To extract the diurnal data we need to define "day" and "night" across the whole country, and that is valid for all seasons. We could make the data seasonally dependent, but that requires a little more effort that was not considered sufficiently important given that the length of days does not change significantly in the tropics. We have defined a day to be the smallest subset of times when it is light across the whole continent in Winter, from 8AM in Western Australia until 5pm on the East coast. We define a night to be the smallest subset of times when it is dark across the whole continent in Summer, from 8pm on the West coast until 5am on the East coast. This is not taking daylight savings time into account, as we actually work in Universal Time with these images, i.e. day is taken to be 0000UT – 0700UT and night to be 1200UT – 1900UT, as seen in the code `daynight_im_sorter.py`. Inspection of a selection of images suggests that these are reasonable limits.

A.5.1 Seasonal Image Sorter

```
#This script copies images from the main set into a subdirectory
for summer images (December, January and February); winter images
(June, July and August); and the shoulder seaons (here, April
and October).


import subprocess
```

```
import os
import sys

workdir = "/arch/cehotan/BoM_ftp/IDE05"
os.chdir(workdir)
print subprocess.Popen([r"pwd"])

print "Copying files in December, January and February in to
/arch/cehotan/BoM_ftp/IDE05/Summer/."
#Summer images
subprocess.Popen([r"cp IDE00005.20??12*.gif Summer/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??01*.gif Summer/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??02*.gif Summer/"],shell=True)


print "Copying files in June, July and August in to
/arch/cehotan/BoM_ftp/IDE05/Winter/."
#Winter images
subprocess.Popen([r"cp IDE00005.20??06*.gif Winter/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??07*.gif Winter/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??08*.gif Winter/"],shell=True)

print "Copying files in April and October in to
/arch/cehotan/BoM_ftp/IDE05/Shoulder/."
#Shoulder season images
subprocess.Popen([r"cp IDE00005.20??04*.gif Shoulder/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??10*.gif Shoulder/"],shell=True)

#End of script
```

A.5.2 Diurnal Image Sorter

```
#This script copies images from the main set into a subdirectory
for day images (smallest subset in winter, start 8am WA, end 5pm
AEST) and night images (smallest subset in summer start 8pm WA
end 5am AEST).
#Daylight savings matter, so these hours equate to:
#Day images: 0000UT - 0700UT
#Night images: 1200UT - 1900UT

import subprocess
import os
import sys

workdir = "/arch/cehotan/BoM_ftp/IDE05"
os.chdir(workdir)
print subprocess.Popen([r"pwd"])

print "Copying daytime files to
/arch/cehotan/BoM_ftp/IDE05/Day/."
#Day images
subprocess.Popen([r"cp IDE00005.20??????00*.gif Day/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??????01*.gif Day/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??????02*.gif Day/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??????03*.gif Day/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??????04*.gif Day/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??????05*.gif Day/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??????06*.gif Day/"],shell=True)

print "Copying nighttime files to
```

```
/arch/cehotan/BoM_ftp/IDE05/Night/."
#Night images
subprocess.Popen([r"cp IDE00005.20??????12*.gif Night/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??????13*.gif Night/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??????14*.gif Night/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??????15*.gif Night/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??????16*.gif Night/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??????17*.gif Night/"],shell=True)
subprocess.Popen([r"cp IDE00005.20??????18*.gif Night/"],shell=True)

#End of script
```

Appendix B

Map of Radio and Optical Telescopes in Australia

Here we present a map of Australia showing nearly all research–grade radio and optical telescopes. This information was obtained by hand using common websites such as Wikipedia®[1] in conjunction with Google Earth™ and Google Maps™. Lists of telescopes such as those registered with the IAU Minor Planet Centre are readily available, as are lists of astronomical societies and outreach facilities. As some of the data associated with these layers are personally identifiable, the raw dataset is not included here, nor is it made publicly available in any form, this map simply serves to demonstrate general geographic trends in telescope siting.

The radio telescopes cover research telescopes such as those owned by the CSIRO and universities, as well as major communications installations with dishes large enough to be used for radio astronomy; military installations; present and disused NASA installations, and some amateur facilities.

The optical telescopes include optical and solar research telescopes owned by universities and other large stake–holders; astronomical outreach facilities such as

[1]Wikipedia - the Free Encyclopedia is an online editable encyclopedia operating under the Creative Commons Attribution–ShareAlike Licence, http://en.wikipedia.org.

public observatories and planetariums; amateur astronomical societies and their dark sky sites; telescopes registered with the International Astronomical Union's Minor Planet Centre and the Astronomical Society of Australia's "Designated Observatory" register; and finally privately owned optical telescopes which are of significant enough aperture to be housed in a dome or "roll–off roof observatory" and are readily found through links of Australian observatories. This is the dataset for which privacy concerns dominate, as many private observatories are built in amateur astronomers' yards. Without the raw data, however, these concerns may be allayed with the low resolution of the map in Figure B.1.

Figure B.1 shows the sites of all current, historical, defunct, and in some cases future observatory facilities, although these are coloured according only to whether they are radio or optical. Note that the proposed site for the Square Kilometre Array (SKA) in Australia is centred on an area in the Murchison region of Western Australia. This area has been declared a Radio Quiet Zone (RQZ) by the Australian Communications and Media Authority (ACMA Spectrum Planning Branch, 2007), prohibiting Radio Frequency transmission within a 100–150km radius of the centre of the site (marked as a single point). This area currently houses the developmental stages of the Murchison Widefield Array (MWA) (Lonsdale et al., 2009) and the Australian SKA Pathfinder (ASKAP) (Johnston et al., 2008).

Figure B.2 shows the sites of all current, historical, defunct *et cetera* optical telescopes, coloured according to usage. Note that the majority of telescopes are small private research telescopes, but the distribution of these is still centred around population areas but away from the cities. Note that teaching sites are typically universities which are based in cities and do not have good sky conditions but provide learning aids to school and university students, while the "outreach" category encompasses both public observatories and also planetariums.

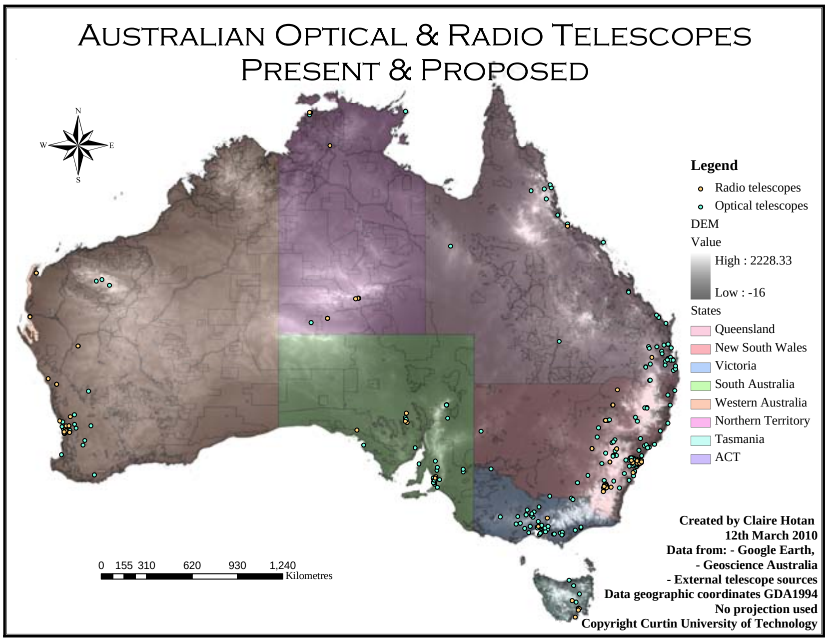

Figure B.1: Optical and radio telescopes in Australia.

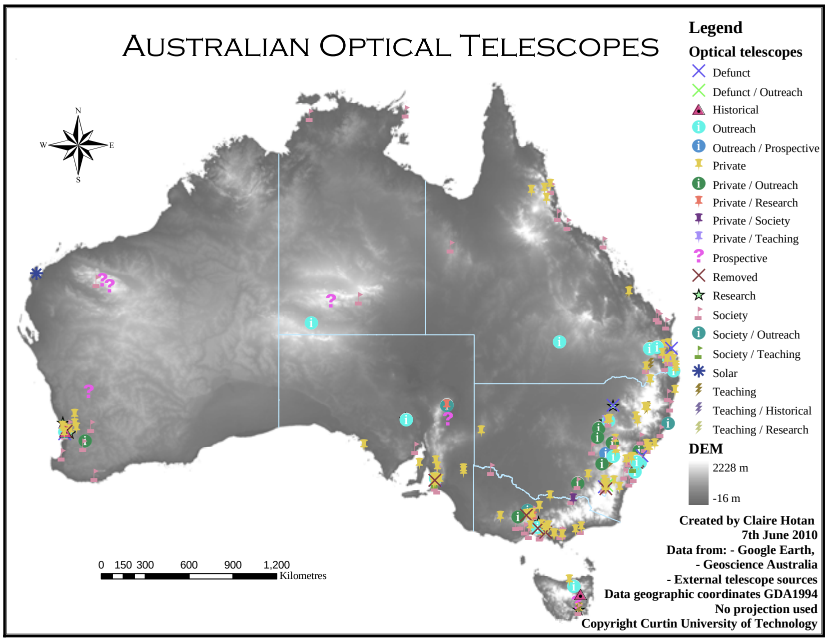

Figure B.2: Optical telescopes in Australia, according to use.

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